Sterile Neutrinos

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BNL Colloquium, 9/30/2014

3 neutrino
oscillation framework

Light sterile neutrino
(or something else
we don't understand)

"JAWS" (1975)
Directed by Steven Spielberg

Outline

- Neutrinos and oscillations
- How do we study neutrino oscillations?
- The sterile neutrino
- Future ideas for probing the sterile neutrino

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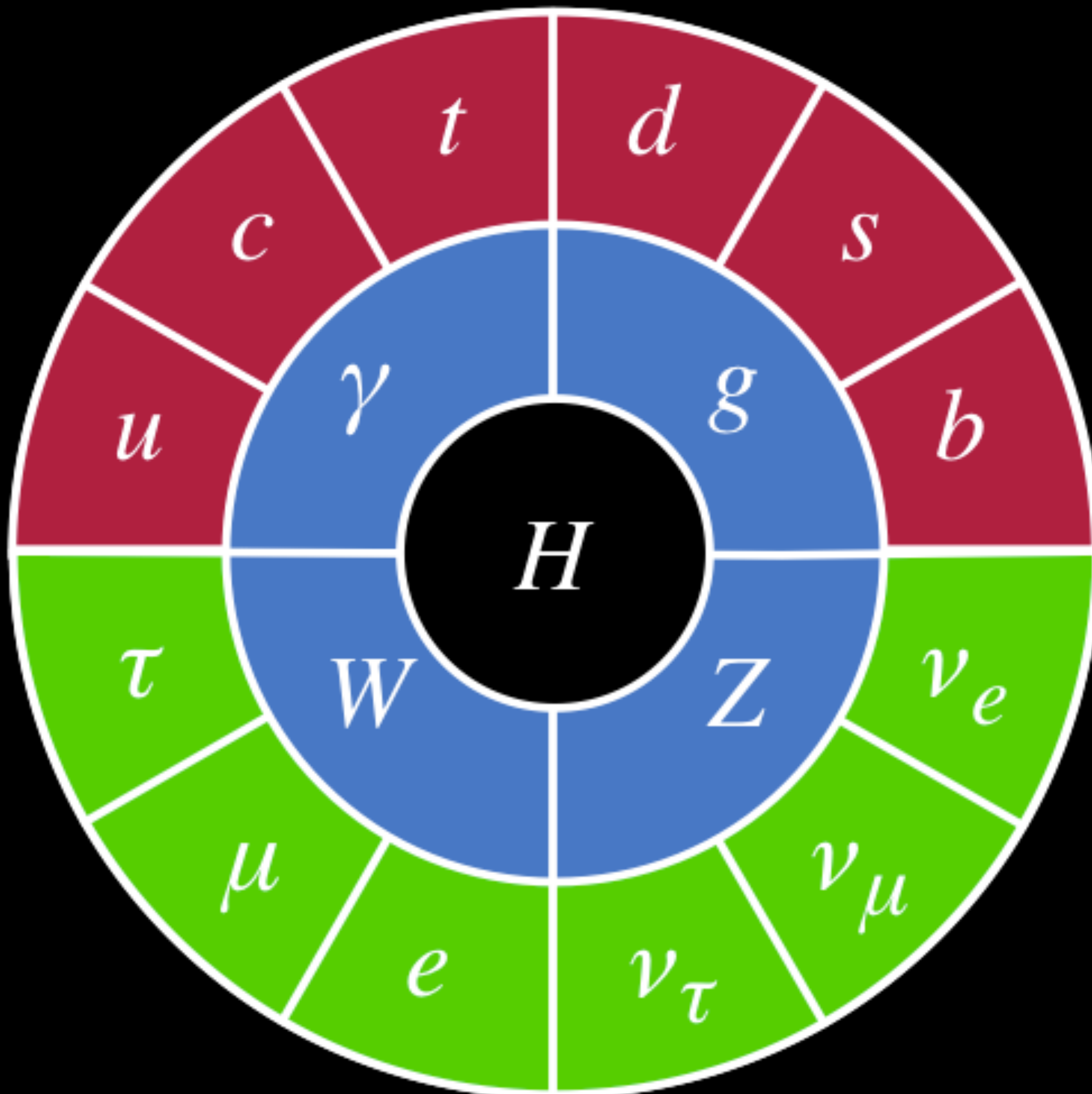


Credit: Particle Fever

Neutrinos come in three flavors

electron

tau

muon

When an X is produced an X neutrino comes with it:

$$n \longrightarrow p + e^{-} + \overline{\nu}_e$$

When an X neutrino interacts it produces an X:

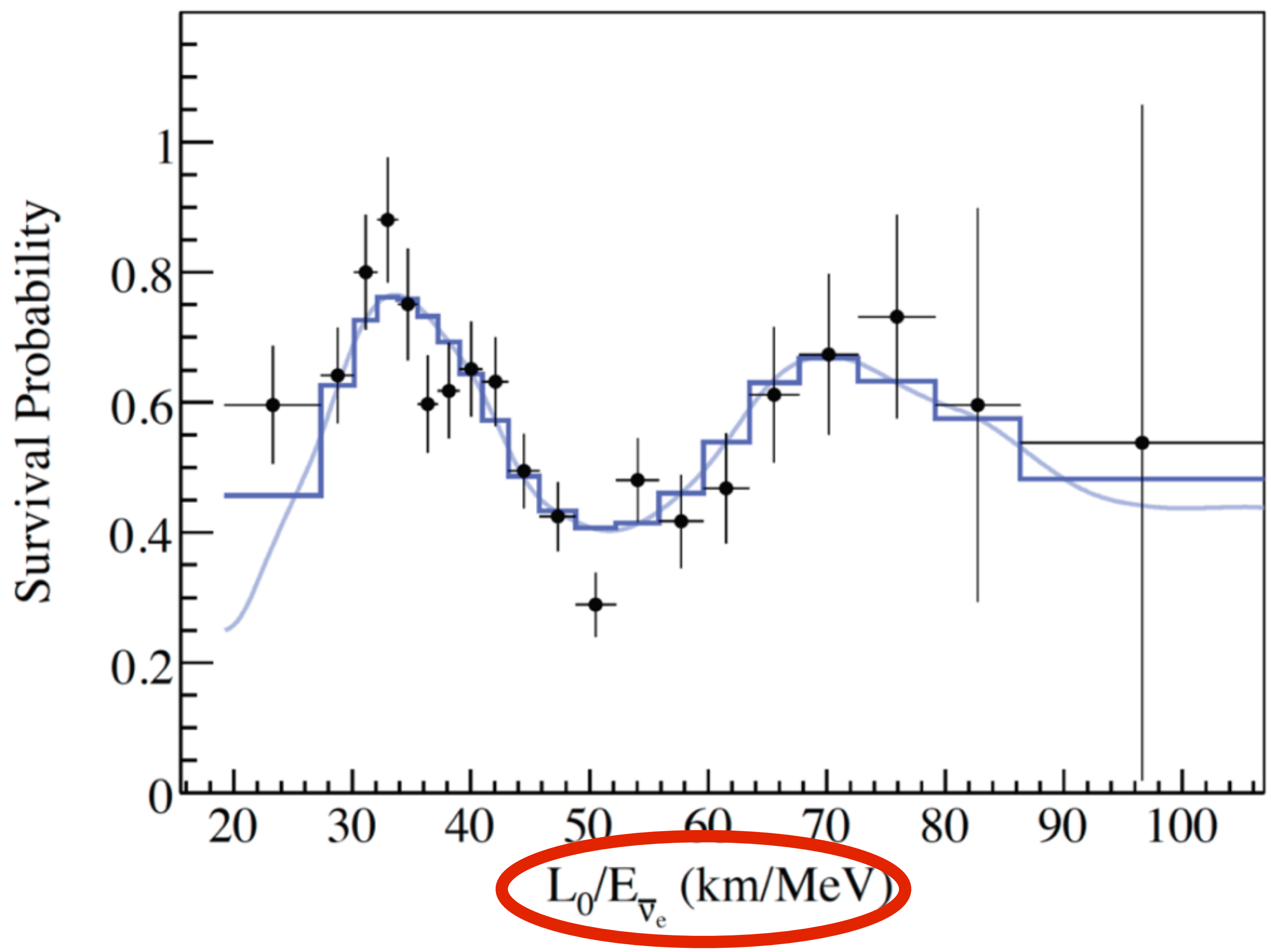
$$\nu_e + n \longrightarrow p + e^{-}$$

Neutrinos change flavor

distance traveled

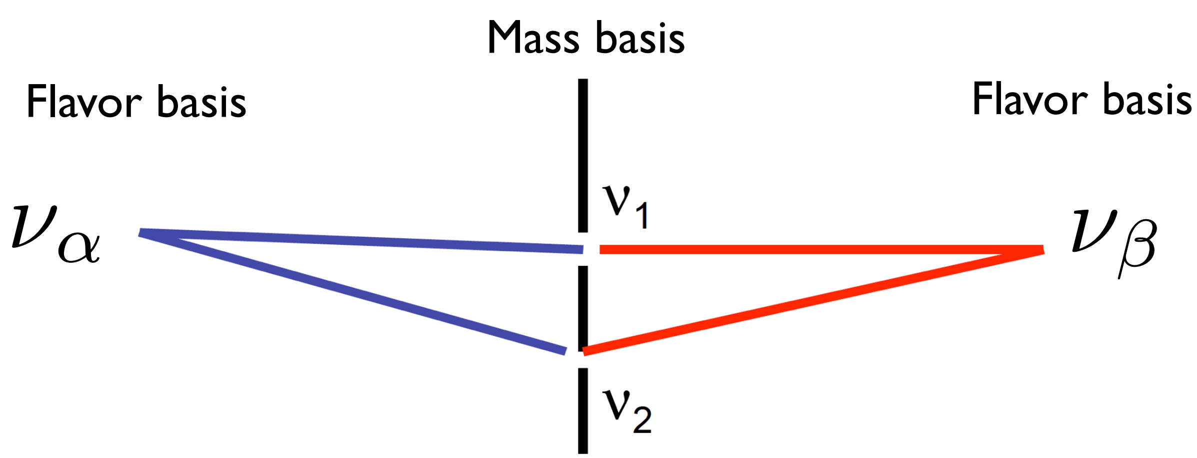
$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\ \sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right)$$

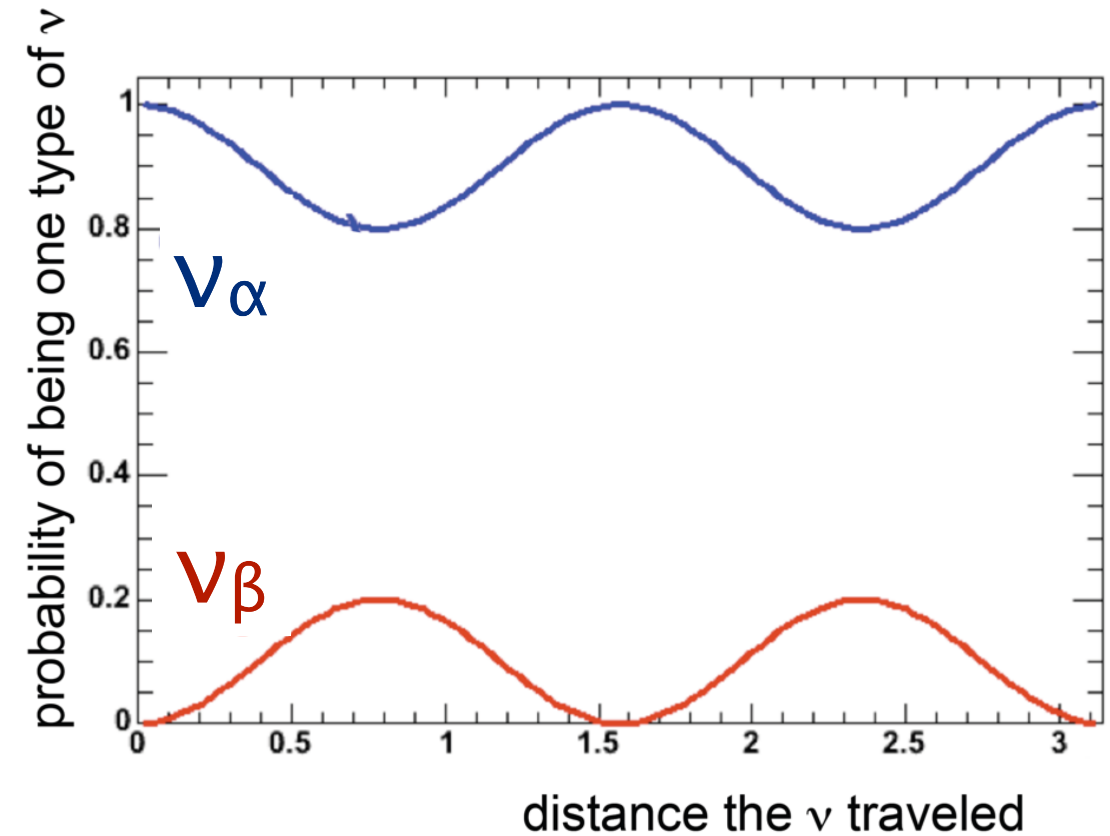
energy



Two neutrino oscillation

Neutrino oscillations are due to a mismatch between the neutrino's mass eigenstate and flavor eigenstate





A "rotation" matrix between mass and flavor describes this:

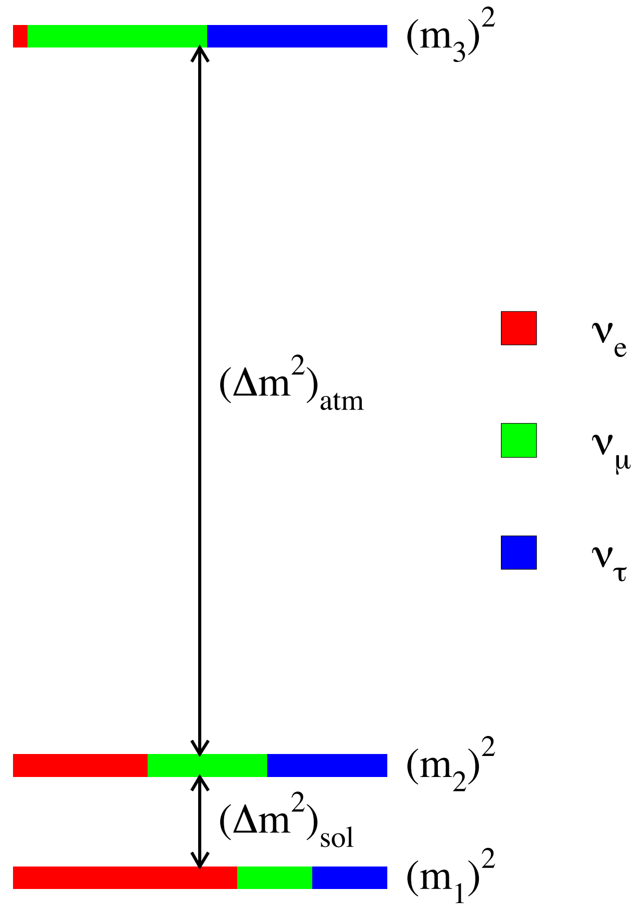
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

A neutrino created as flavor α can be observed sometime later as a neutrino of flavor β.

The neutrino oscillation picture

Atmospheric neutrinos
Solar neutrinos
Accelerator neutrinos
Reactor neutrinos

} Well established oscillations



- Almost all of the oscillation results fit nicely within the three neutrino picture (two mass splittings and three mixing angles).
- Neutrinos from different sources are oscillating according to the same rulebook!

Neutrino oscillation is a big deal

and our goal is to study it in order
to understand just how big of a deal it is.

Big Bang
cosmology

How does the sun shine?

Dark matter?

Why is the universe
made of matter?

Nuclear reactors

Supernova evolution

How are the neutrino
masses ordered?

3, 4, 5, 6 neutrinos?

A hidden sector?

neutrino=antineutrino?

Do neutrinos obey
fundamental symmetries?

Heavy element formation

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How to probe neutrino oscillations?

1. Make a lot of neutrinos.
2. Count them.
3. Compare to how many you expected.

How to probe neutrino oscillations?

e.g. for measuring neutrino CP violation

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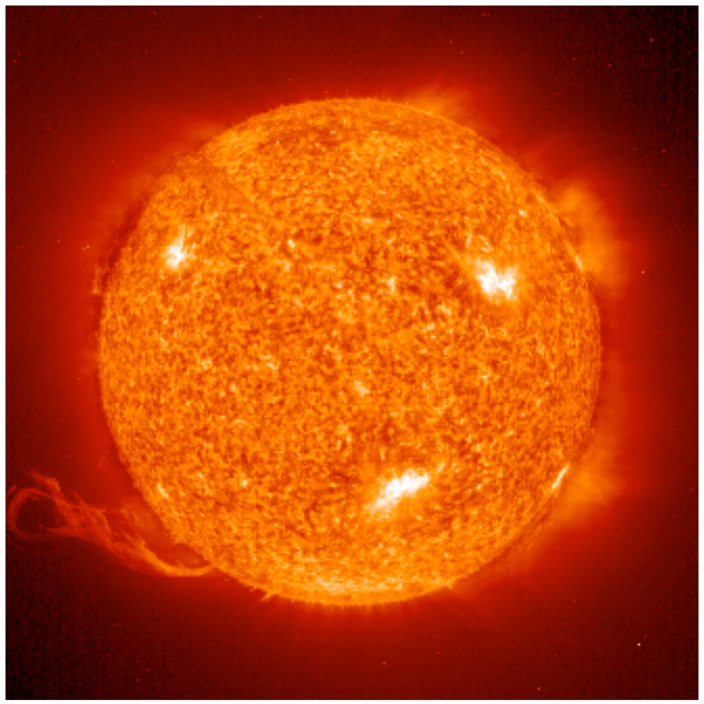
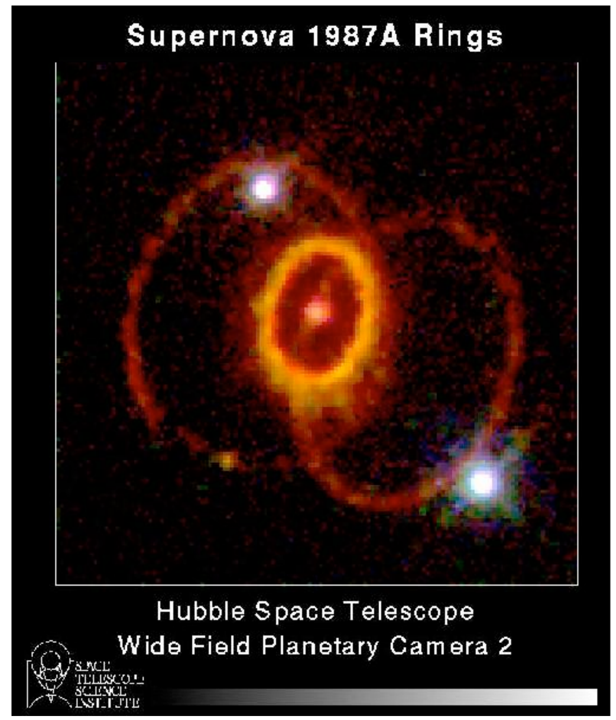
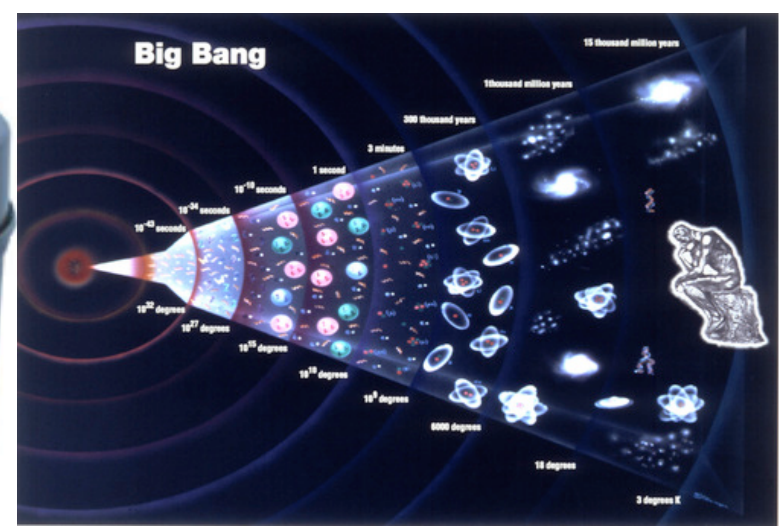
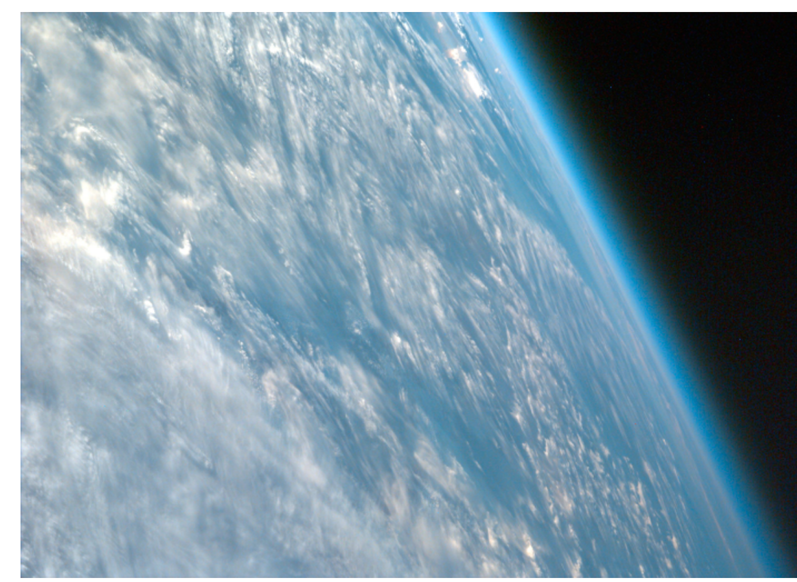
2. Count them.
3. Compare to how many you expected.

Sources of neutrinos

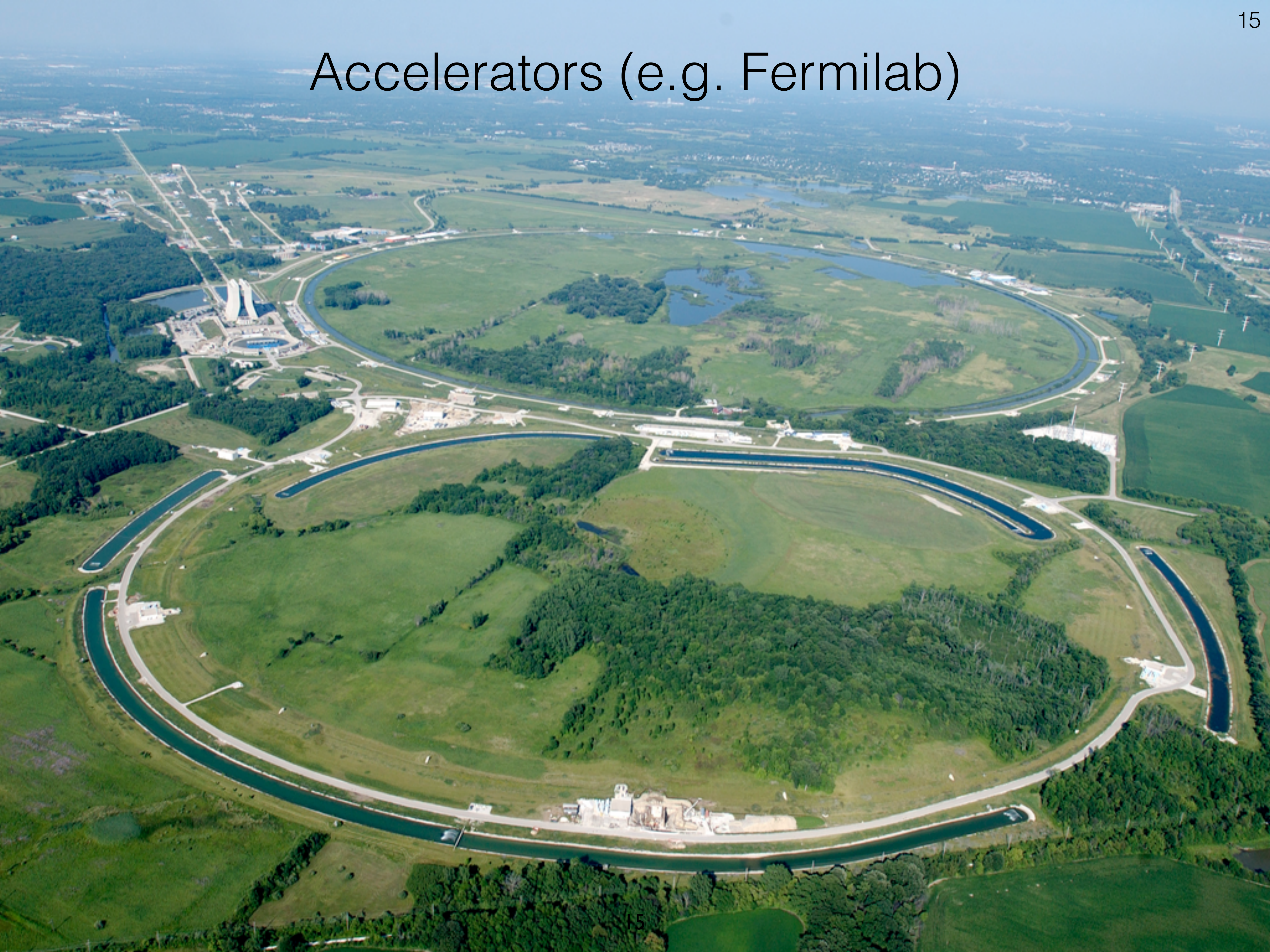




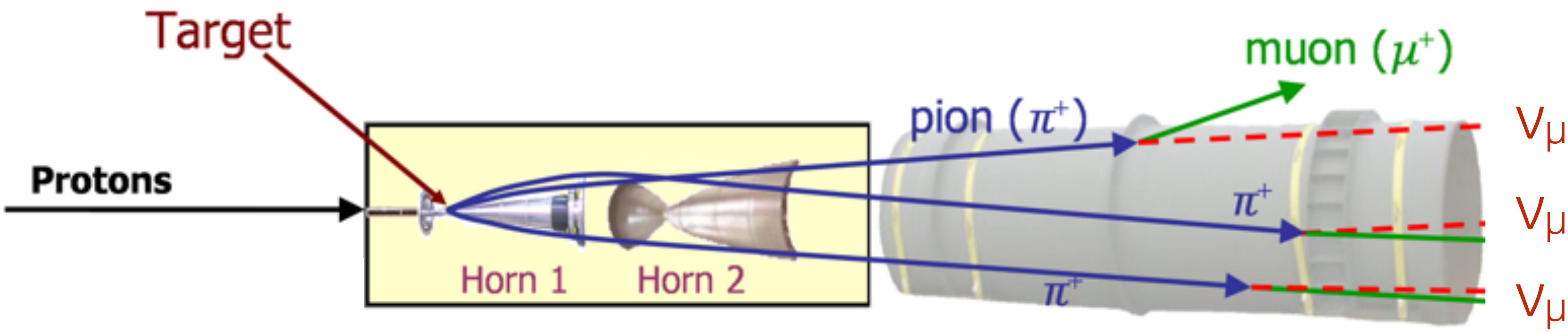




Accelerators (e.g. Fermilab)



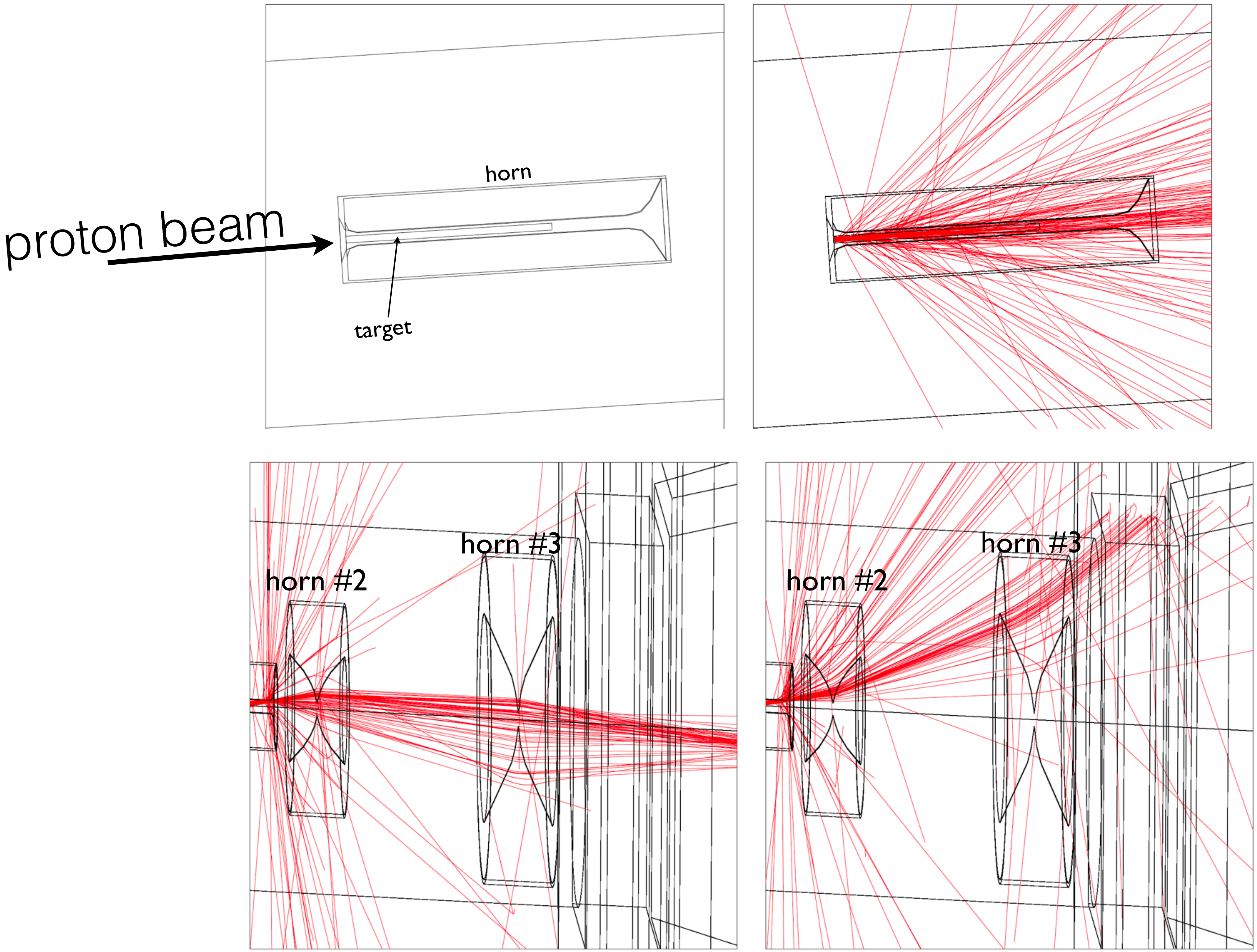
Creating a neutrino beam



Neutrino beam $\pi^+ \to \mu^+ \nu_\mu$

Antineutrino beam $\pi^- \to \mu^- \overline{\nu}_\mu$

Creating a neutrino beam



pion

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\pi^- \rightarrow \mu^- \overline{\nu}_\mu$$

How to probe neutrino oscillations?

1. Make a lot of neutrinos.
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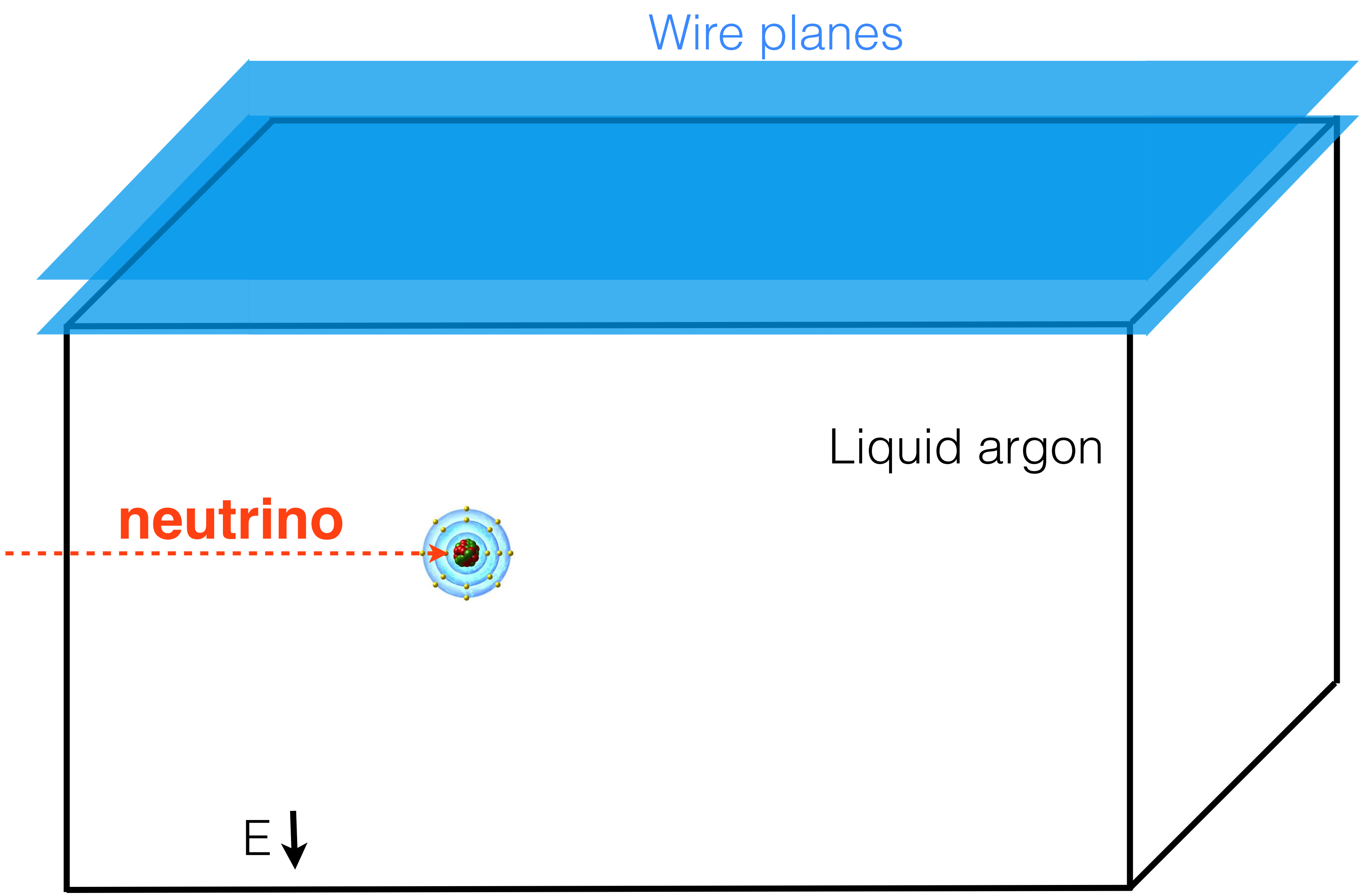
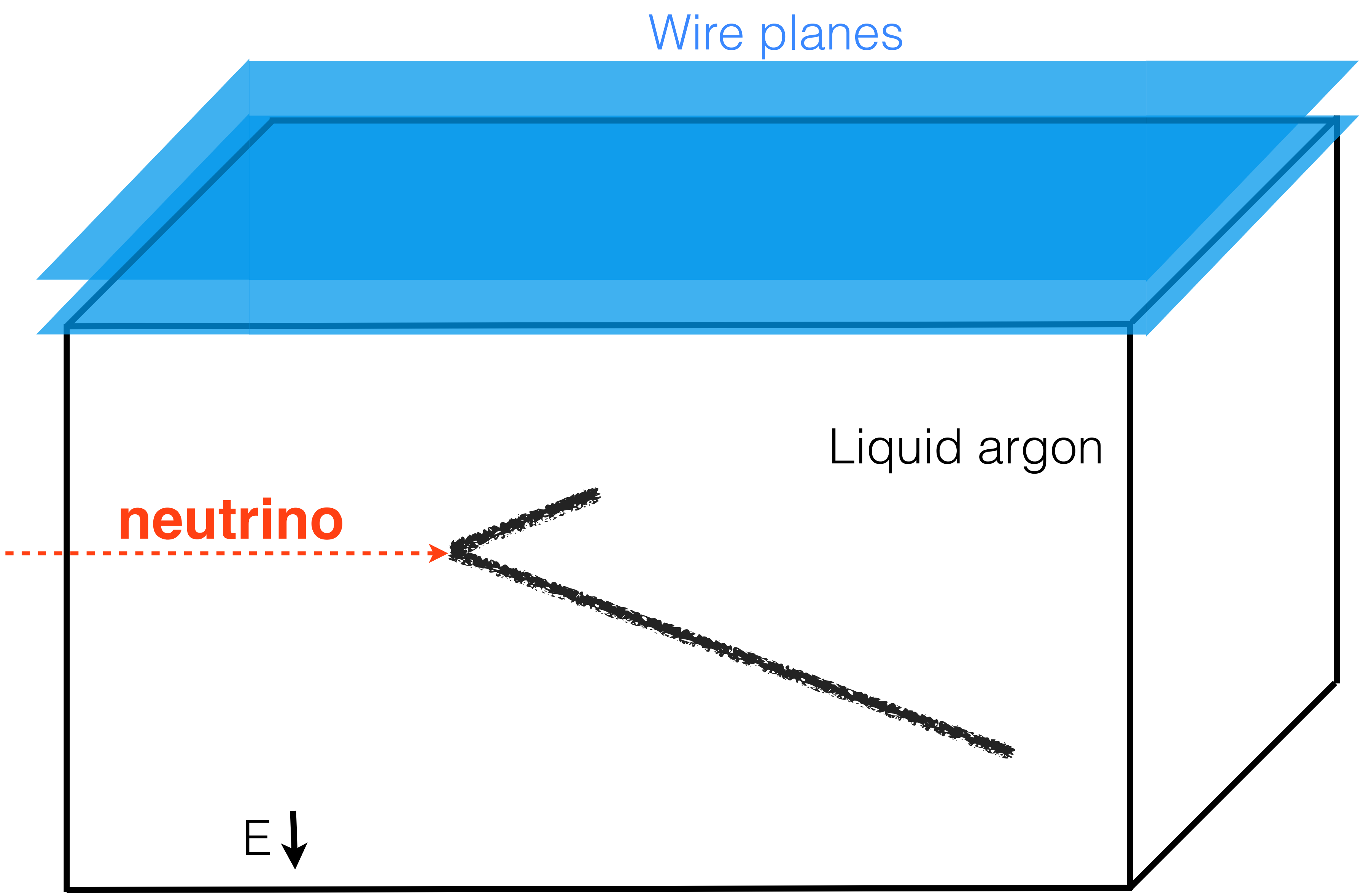
3. Compare to how many you expected.

Liquid Argon Time Projection Chamber



Liquid Argon Time Projection Chamber



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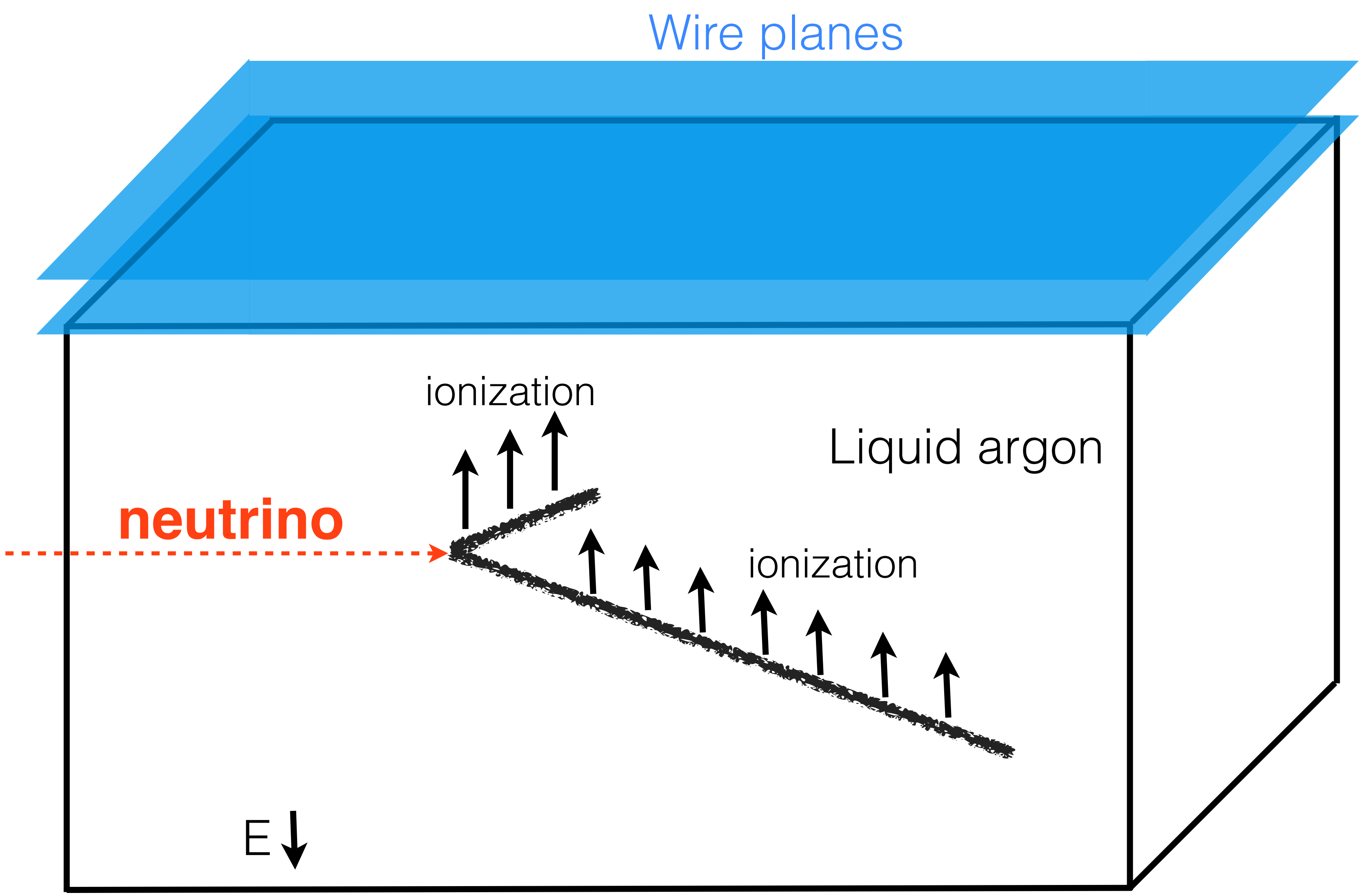

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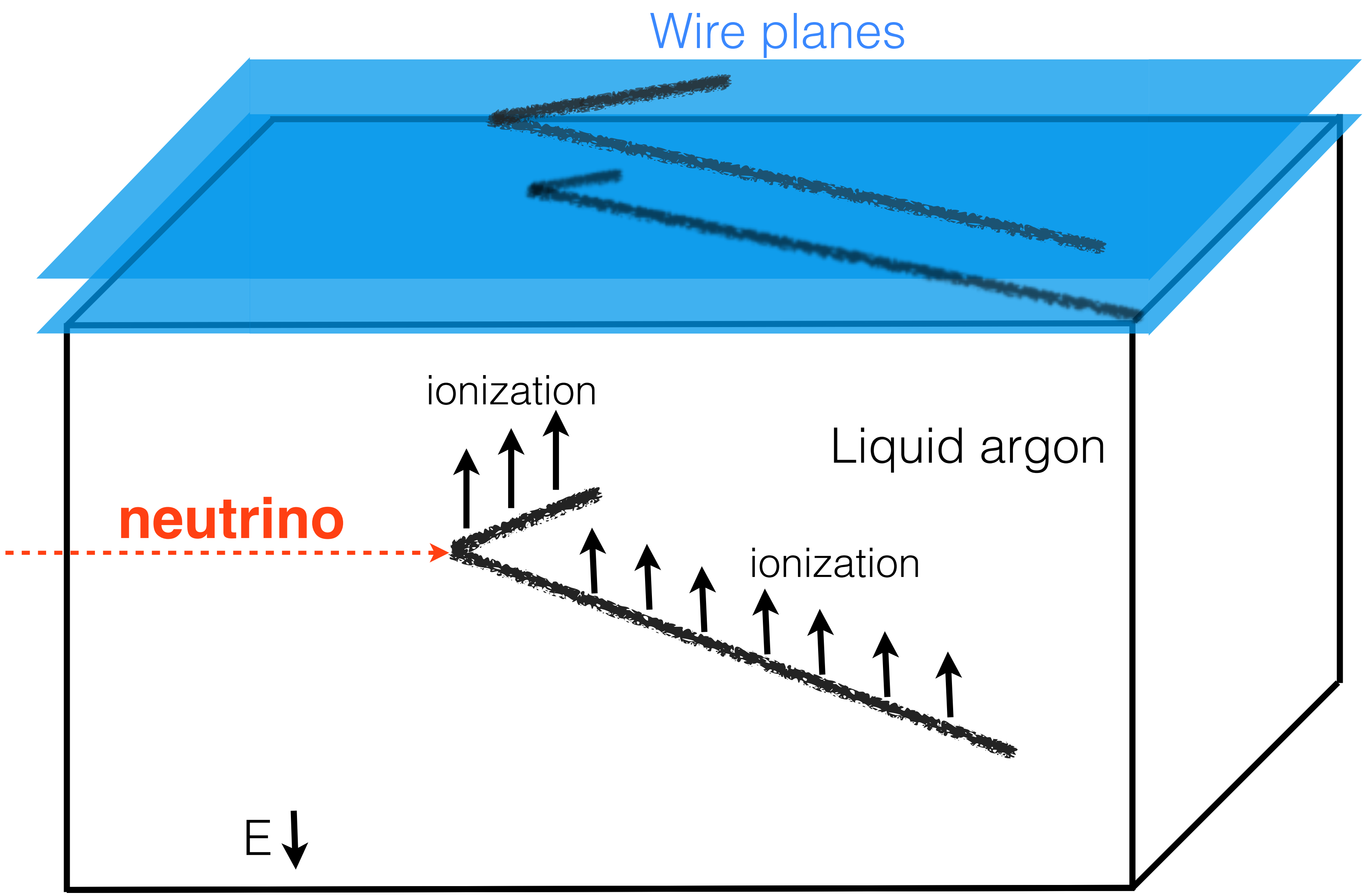
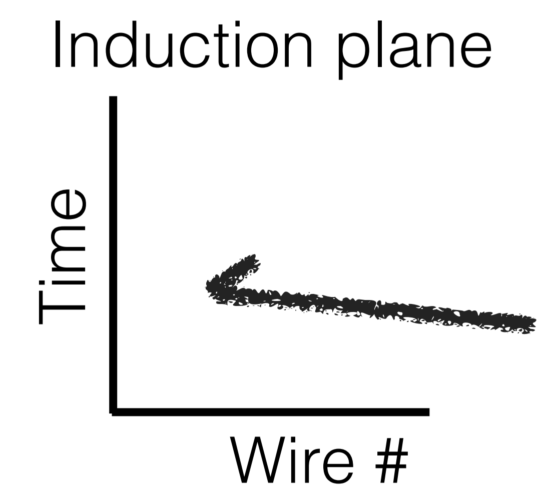
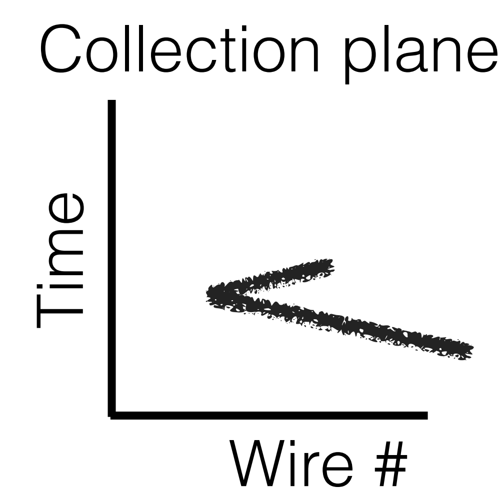
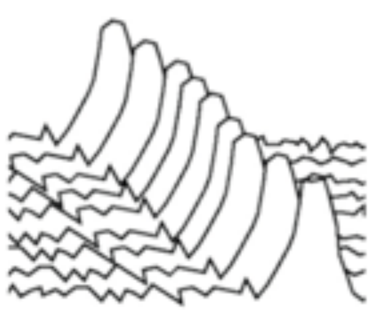




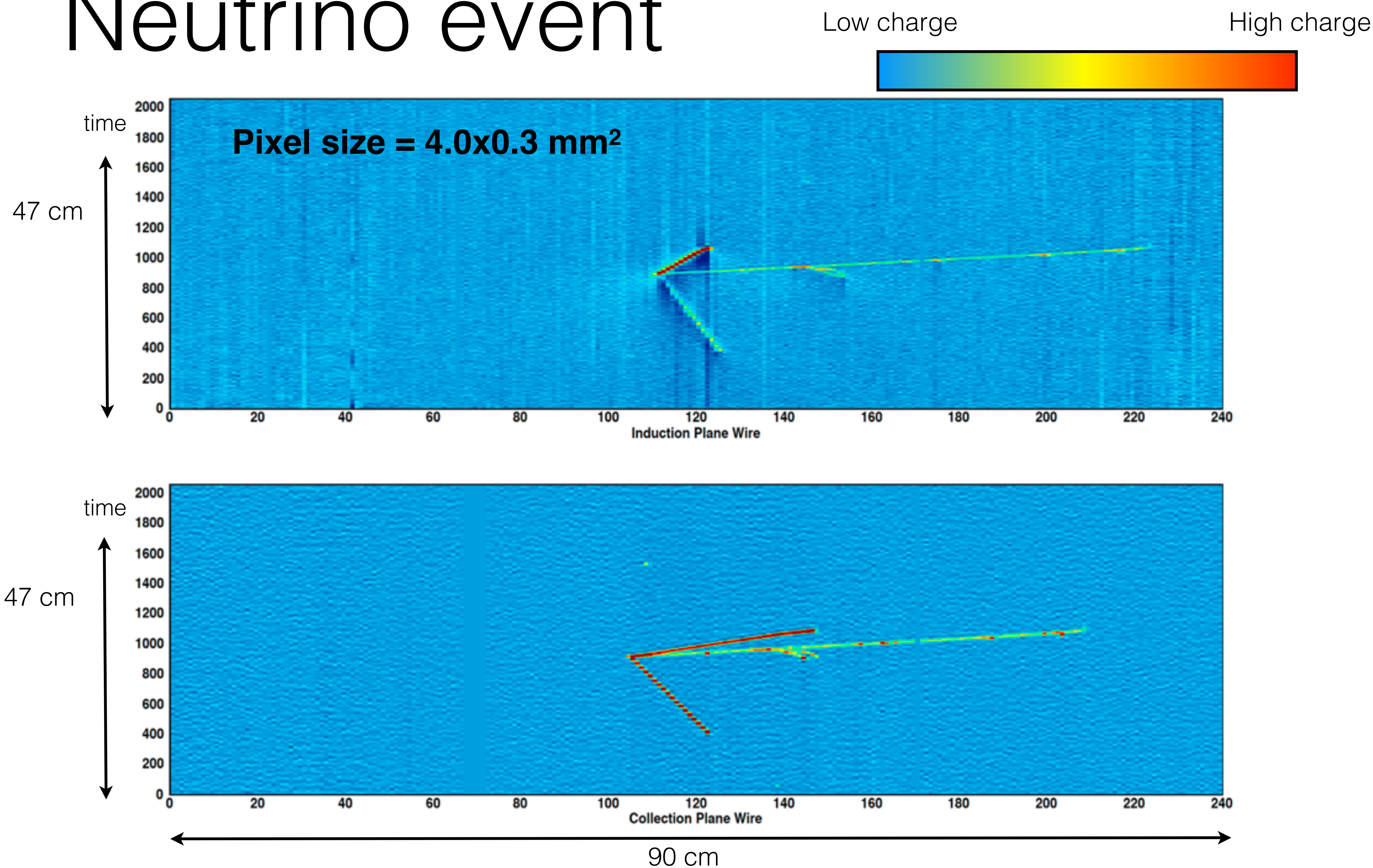




Wire pulses in time give the drift coordinate of the track

induction plane + collection plane + time = 3D image of event (w/ calorimetric info)

Neutrino event



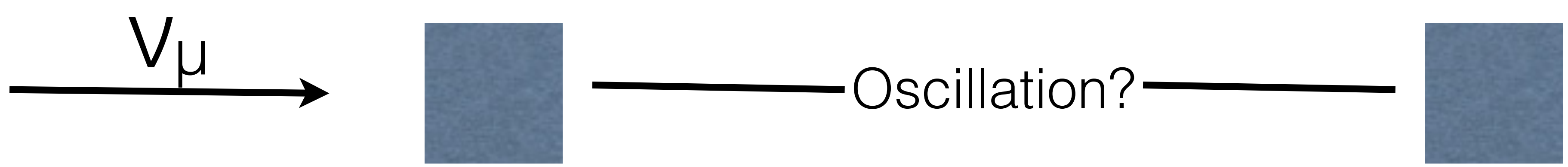
How to probe neutrino oscillations?

1. Make a lot of neutrinos.
2. Count them.
3. Compare to how many you expected.

A conventional long baseline oscillation experiment

Compare these ratios
as a function of energy

$\nu_e : \nu_\mu$? $\longleftrightarrow$ $\nu_e : \nu_\mu$?



near detector
~100s of m

far detector
~100s of km

CP violation in the lepton sector?

$$P[\nu_\mu \to \nu_e] \neq P[\overline{\nu}_\mu \to \overline{\nu}_e] \ ?$$

The path to neutrino CP violation

- The US is pursuing the Long Baseline Neutrino Experiment (LBNE), featuring an envisioned 34 kiloton Liquid Argon Time Projection Chamber (LArTPC) far detector in an accelerator-based neutrino beam.
- There are a lot of challenges along the way.
- Going from 0.3 tons to 34 kilotons is pretty hard.
- There is also a lot of physics along the way too!!


CANDY LAND
A Milton Bradley Game
Candy Castle
Chocolate Swamp
Gloppy
STUCK ON A LICORICE SPACE Lose one turn
King Kandy
Princess Frostine
Snow Flake Lake
Lolly
LOLLIPOP WOODS
Gramma Nutt
STUCK ON A LICORICE SPACE Lose one turn
STUCK ON A LICORICE SPACE Lose one turn
PEANUT ACRES
Licorice Forest
Lord Licorice
GUMDROP PASS
Jolly
GUMDROP MOUNTAINS
RAINBOW TRAIL
To the GINGERBREAD TREE
PEPPERMINT FOREST
Mr. Mint
START


Oscillation Land
δ_{CP}
θ_{23} octant
Mass hierarchy
ν_τ
Sterile ν
Lorentz violation
θ_{13}
Non-standard ν interactions
ν cross sections
ν as a probe of the nucleus
Detector R&D
Chocolate Swamp
Gloppy
STUCK ON A LICORICE SPACE Lose one turn
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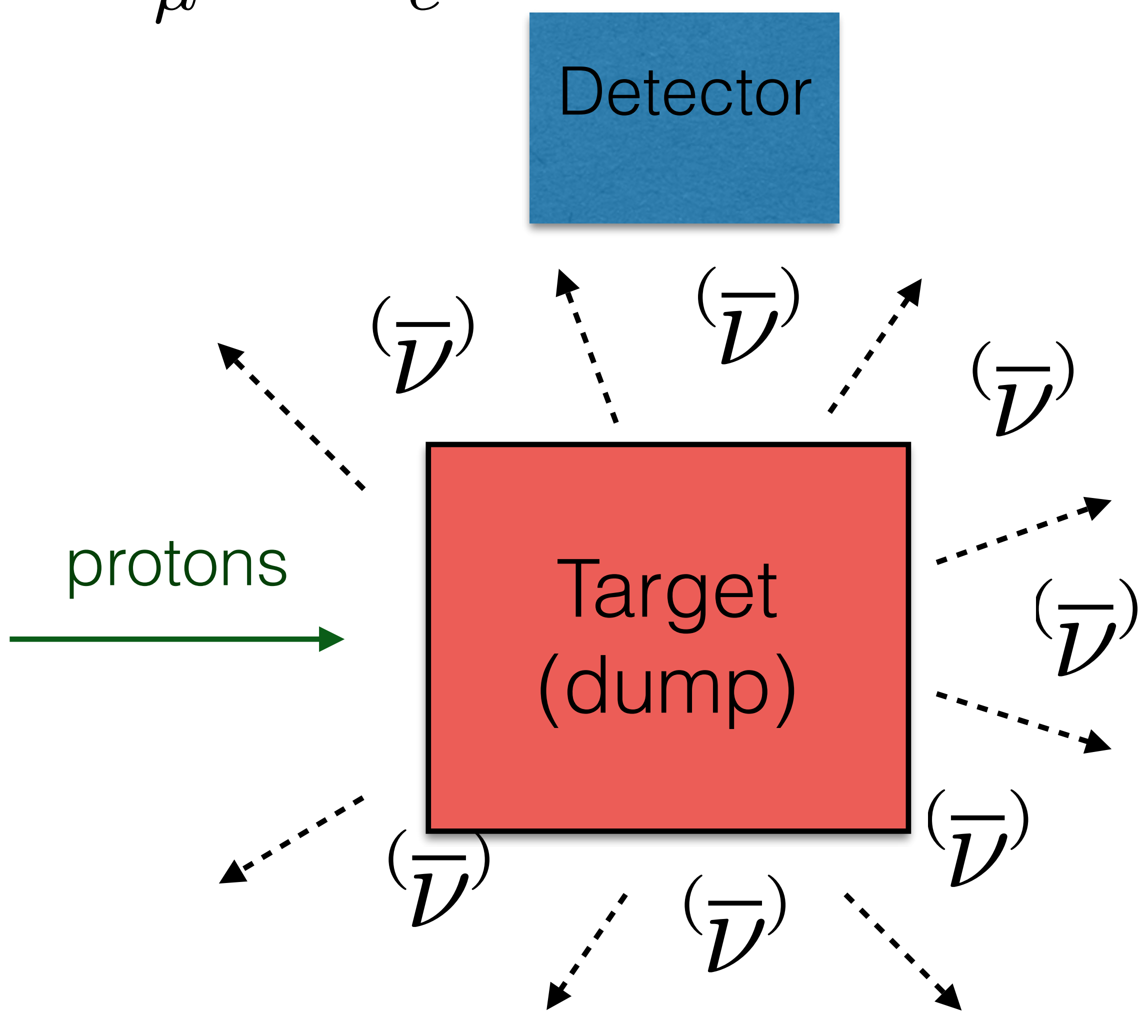
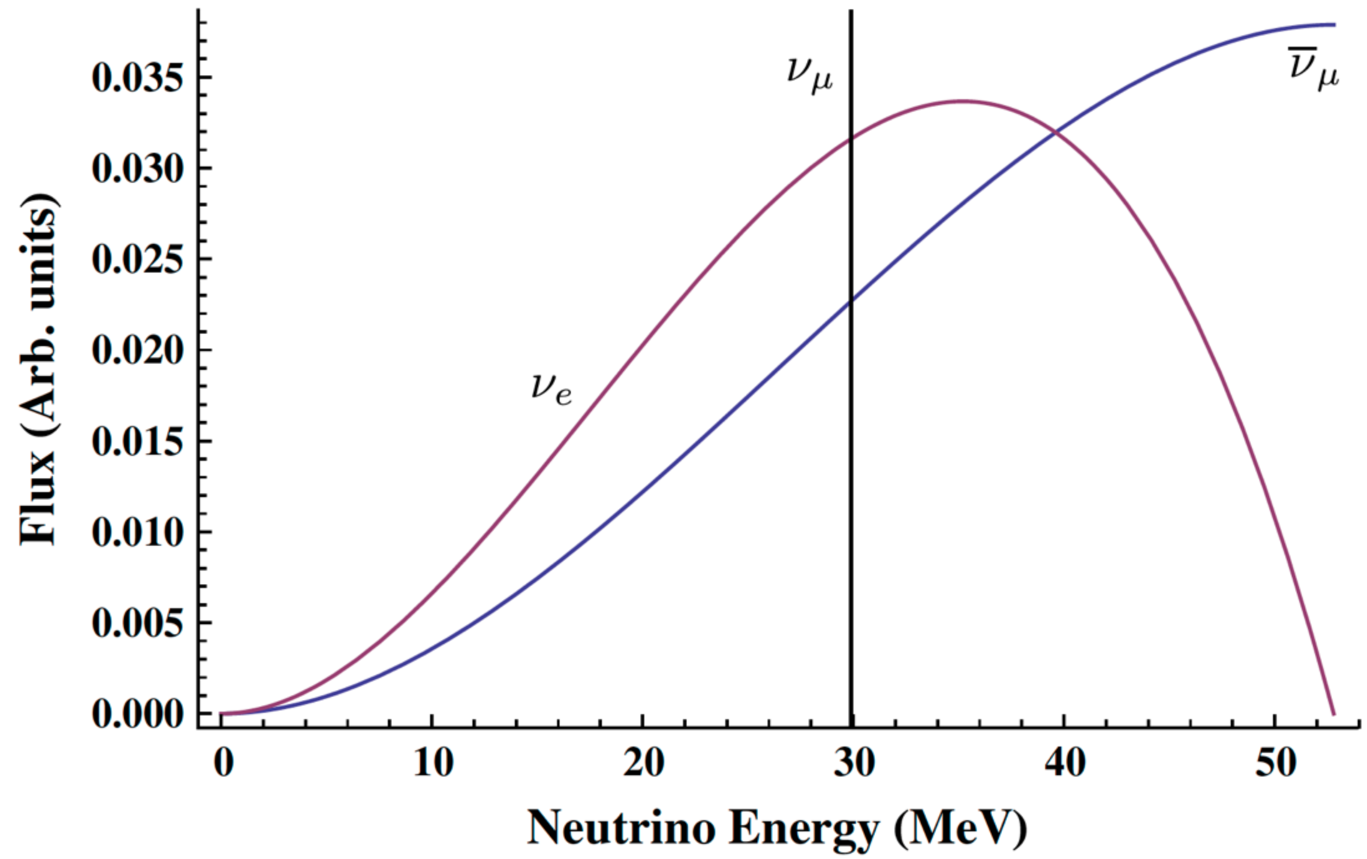
tau-neutrino
STERILE NEUTRINO
electron-neutrino
muon-neutrino

The Liquid Scintillator Neutrino Detector anomaly

Antineutrinos from an accelerator seem to appear!

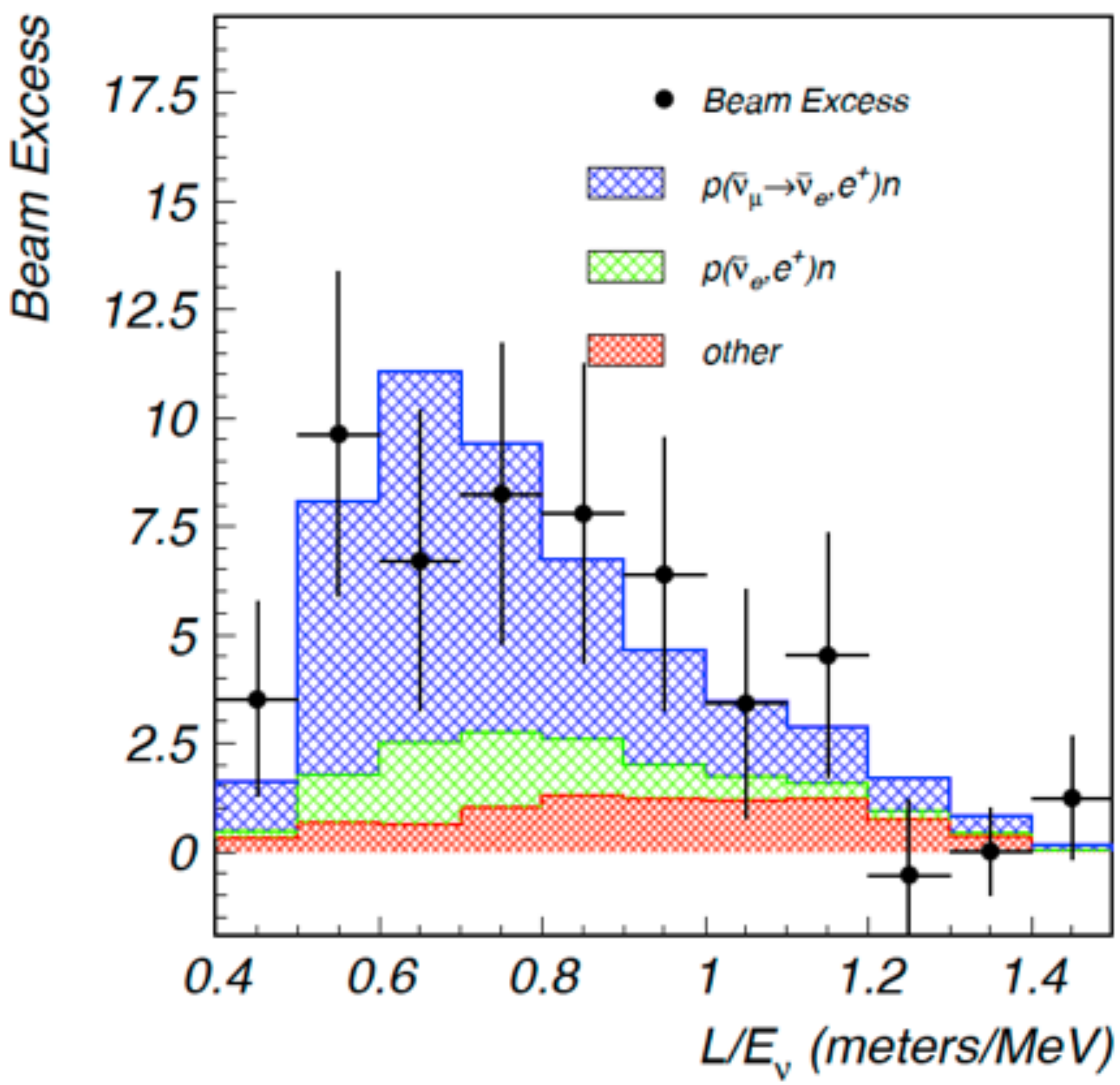
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$?





The Liquid Scintillator Neutrino Detector anomaly

Antineutrinos from an accelerator seem to appear!



- LSND observed $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ at 3.8σ significance with $\Delta m^2 \sim 1$ eV^2.

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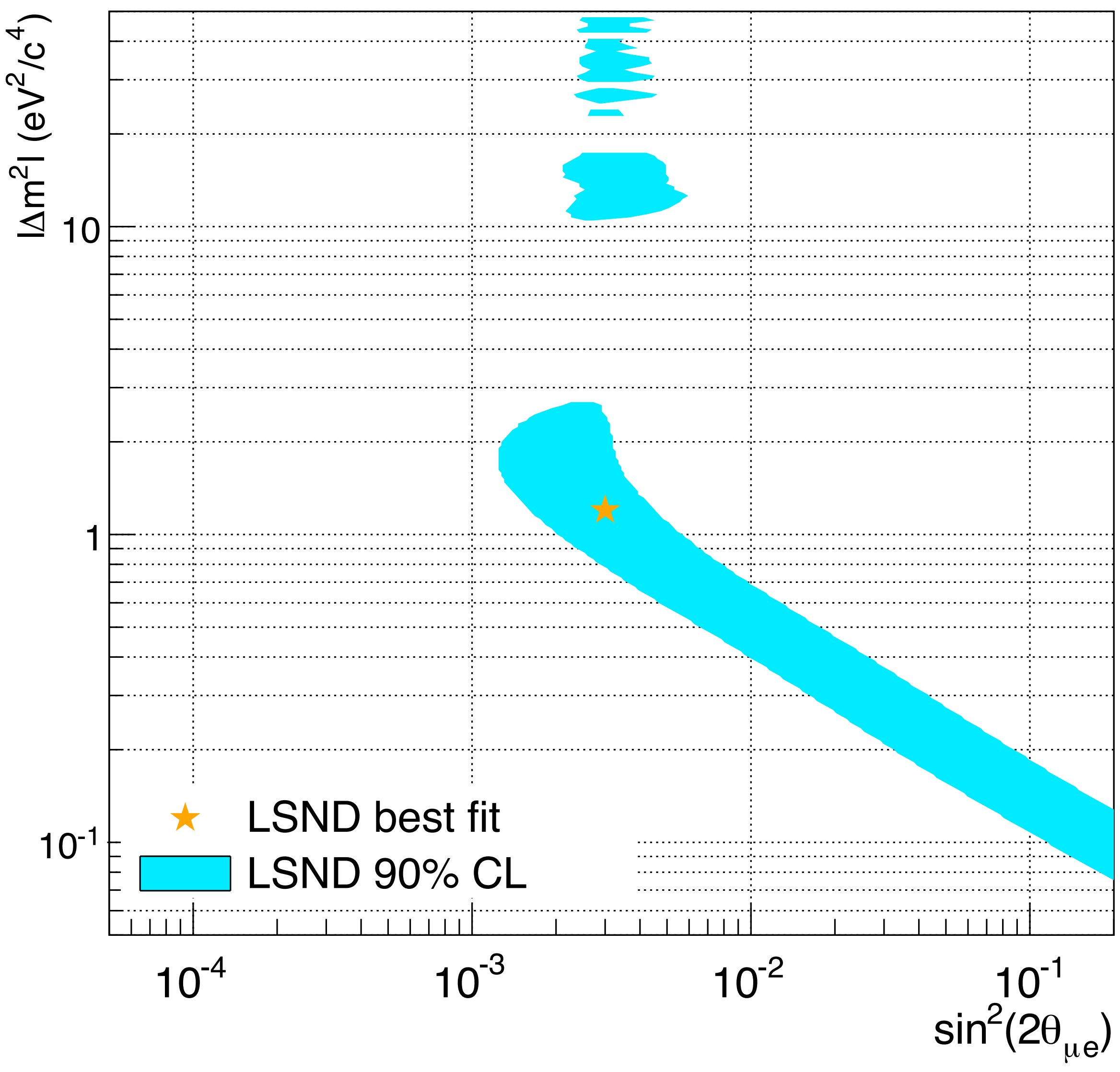
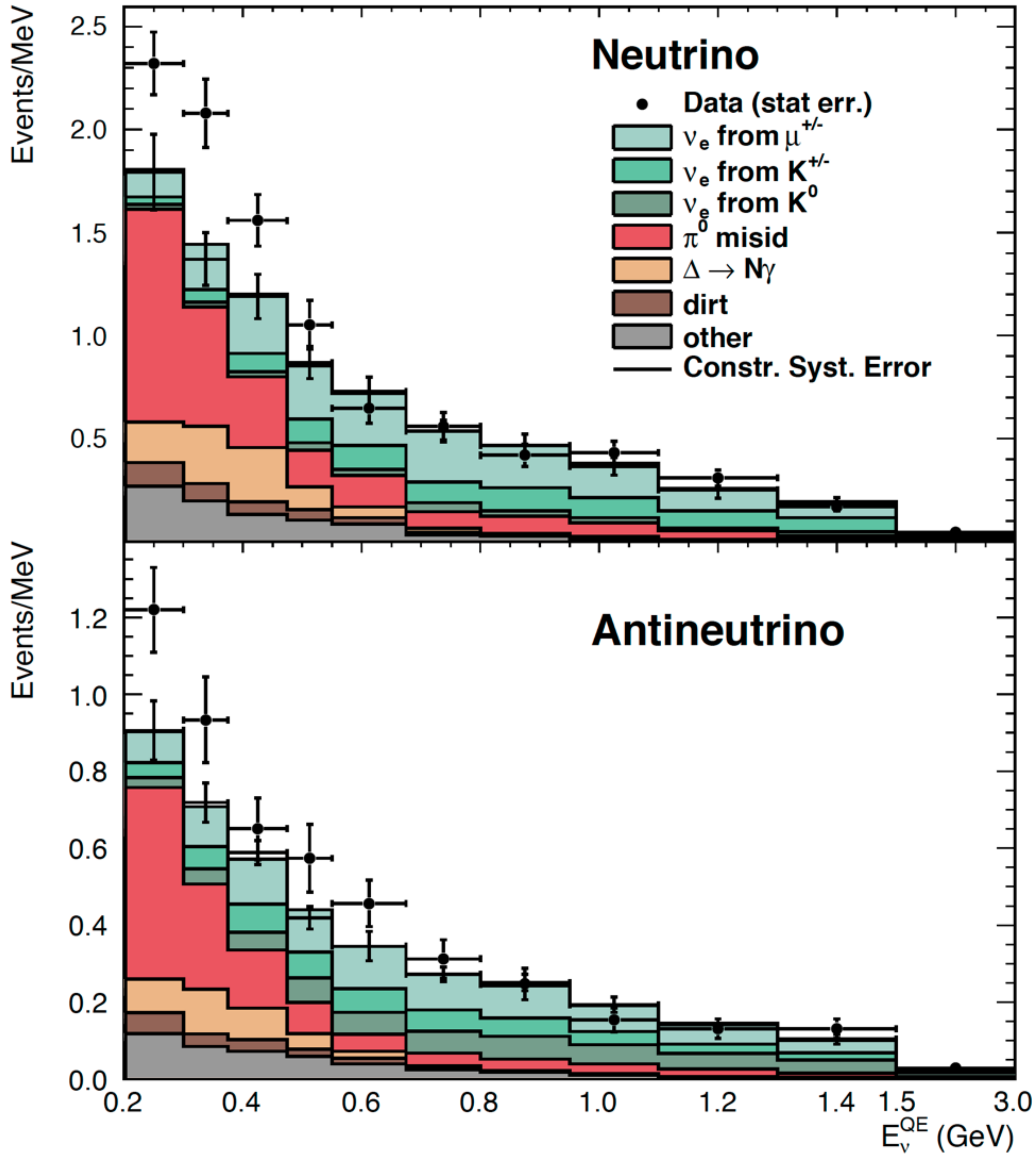


- LSND observed $\overline{\nu}_\mu \to \overline{\nu}_e$ at 3.8σ significance with $\Delta m^2 \sim 1$ eV^2.
- That's odd. There are two independent mass splittings in the three neutrino picture and they are precisely measured.

$$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}})$$

The MiniBooNE anomalies

The MiniBooNE anomalies



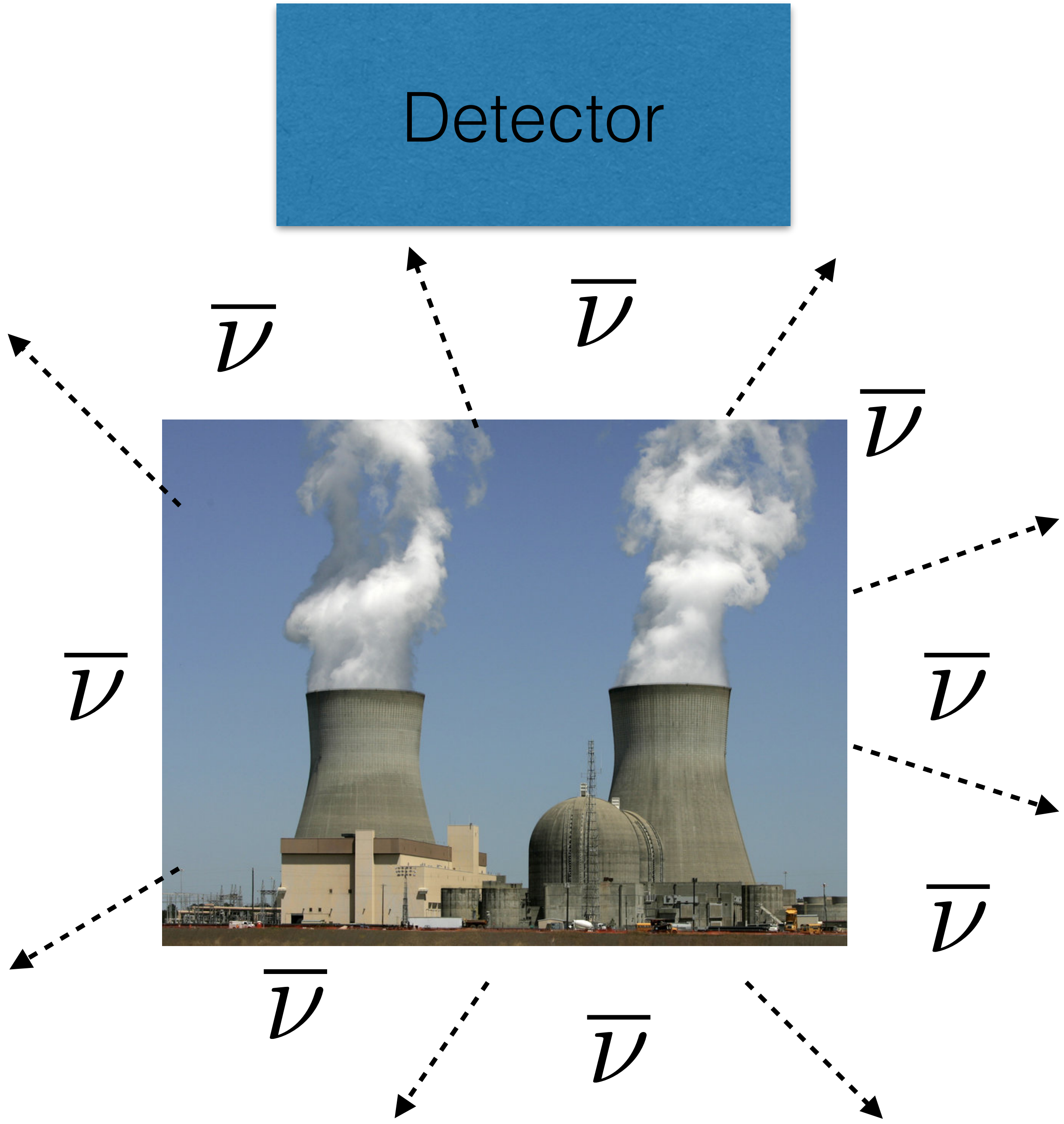
$$\nu_\mu \rightarrow \nu_e$$

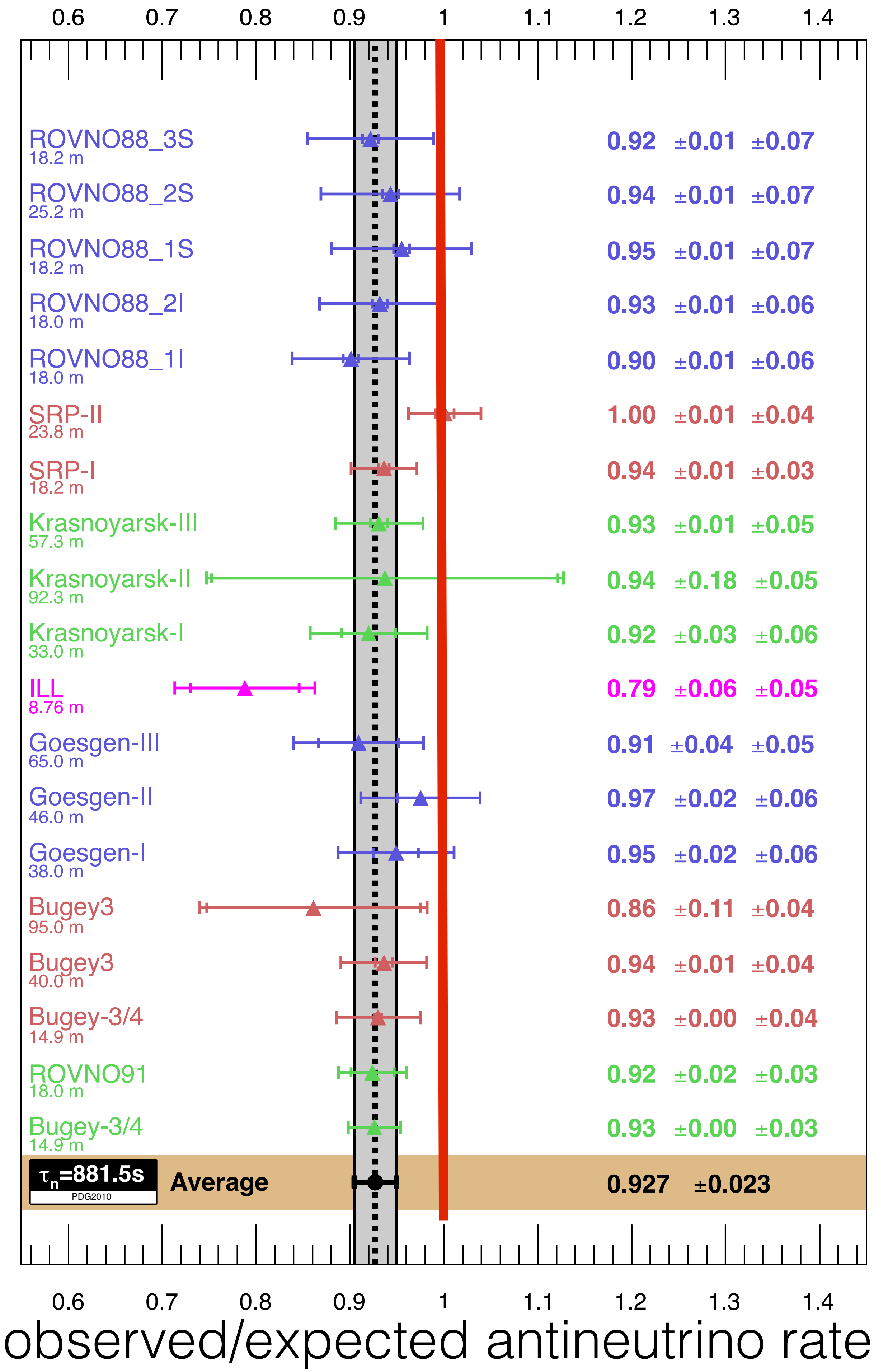
Neutrinos and antineutrinos from an accelerator seem to appear!

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$$

The reactor anomaly

$$\overline{\nu}_e \rightarrow \overline{\nu}_x \; ?$$





The reactor anomaly

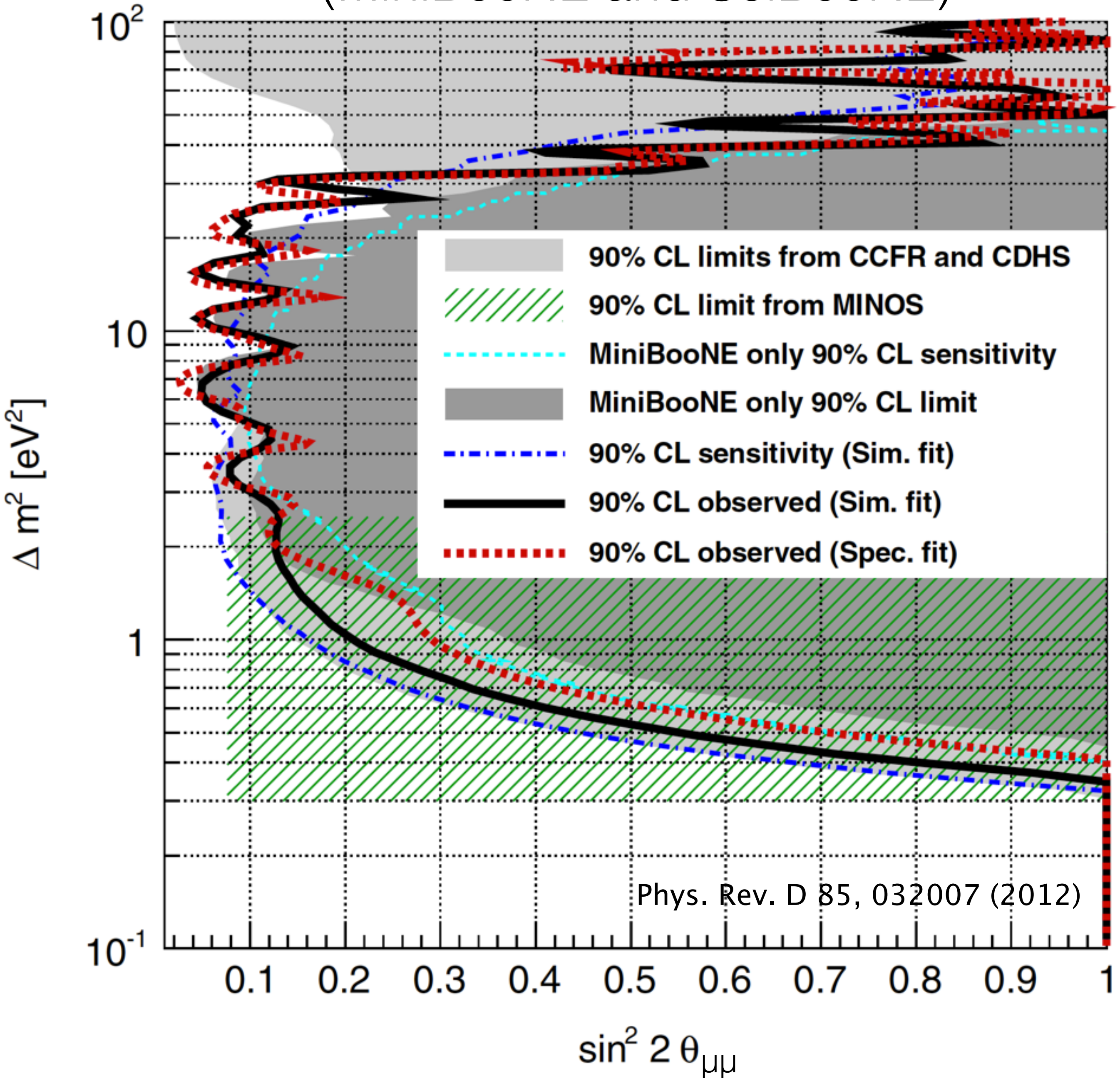
Reactor antineutrinos seem to disappear!

$$\overline{\nu}_e \to \overline{\nu}_x$$

$$0.927 \pm 0.023$$

Limits
(let's not forget)

ν_μ disappearance limits
(MiniBooNE and SciBooNE)

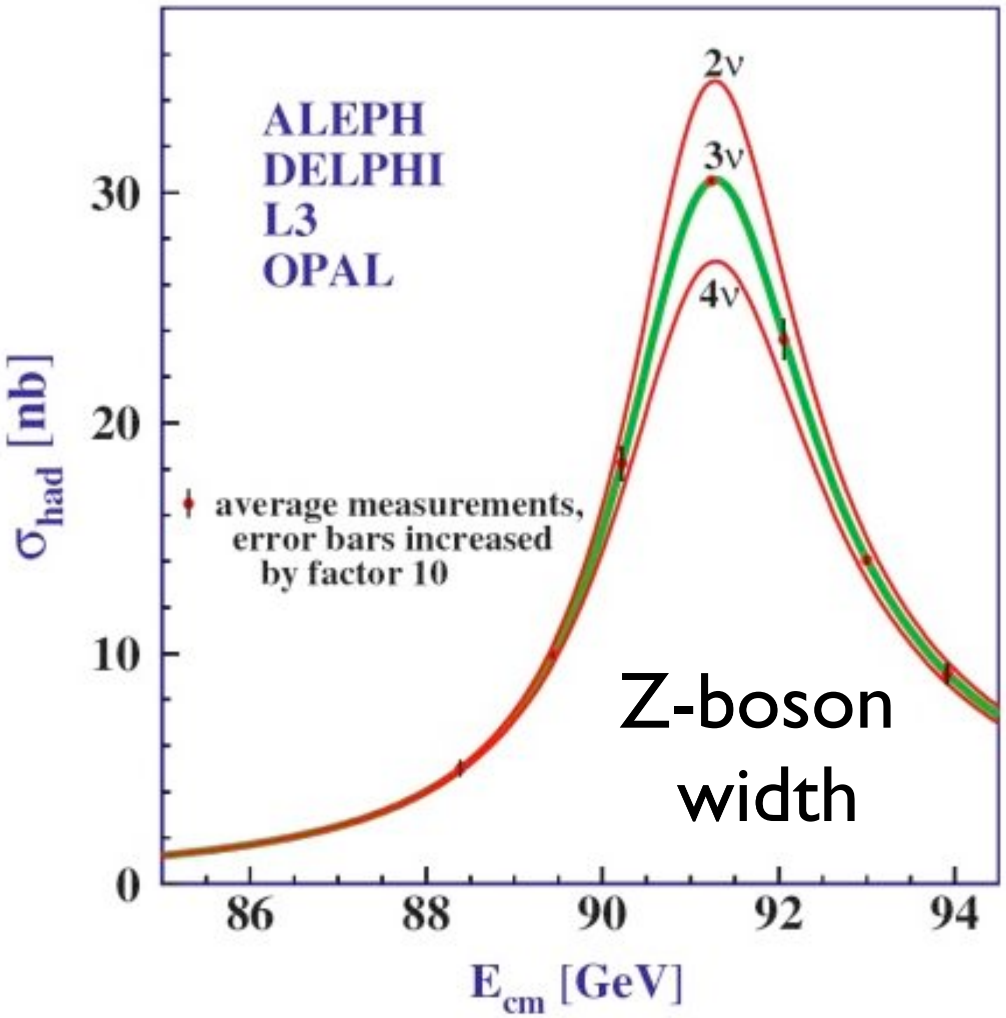


- There do exist a number of strict limits on ν_μ/ν_e disappearance and ν_e appearance in the relevant region.
- In particular, the lack of observed muon neutrino/antineutrino disappearance causes issues when trying to form a coherent picture of the sterile neutrino. In all sterile neutrino scenarios, we expect muon neutrinos to disappear.


(From the “Jaws” movie set;
I don’t think anyone was hurt
as the shark is not real)
Our best efforts to kill
the sterile neutrino
Light sterile neutrino
(or something else
we don’t understand)

If it exists, what is the sterile neutrino?

- Sterile equals no standard model interactions.

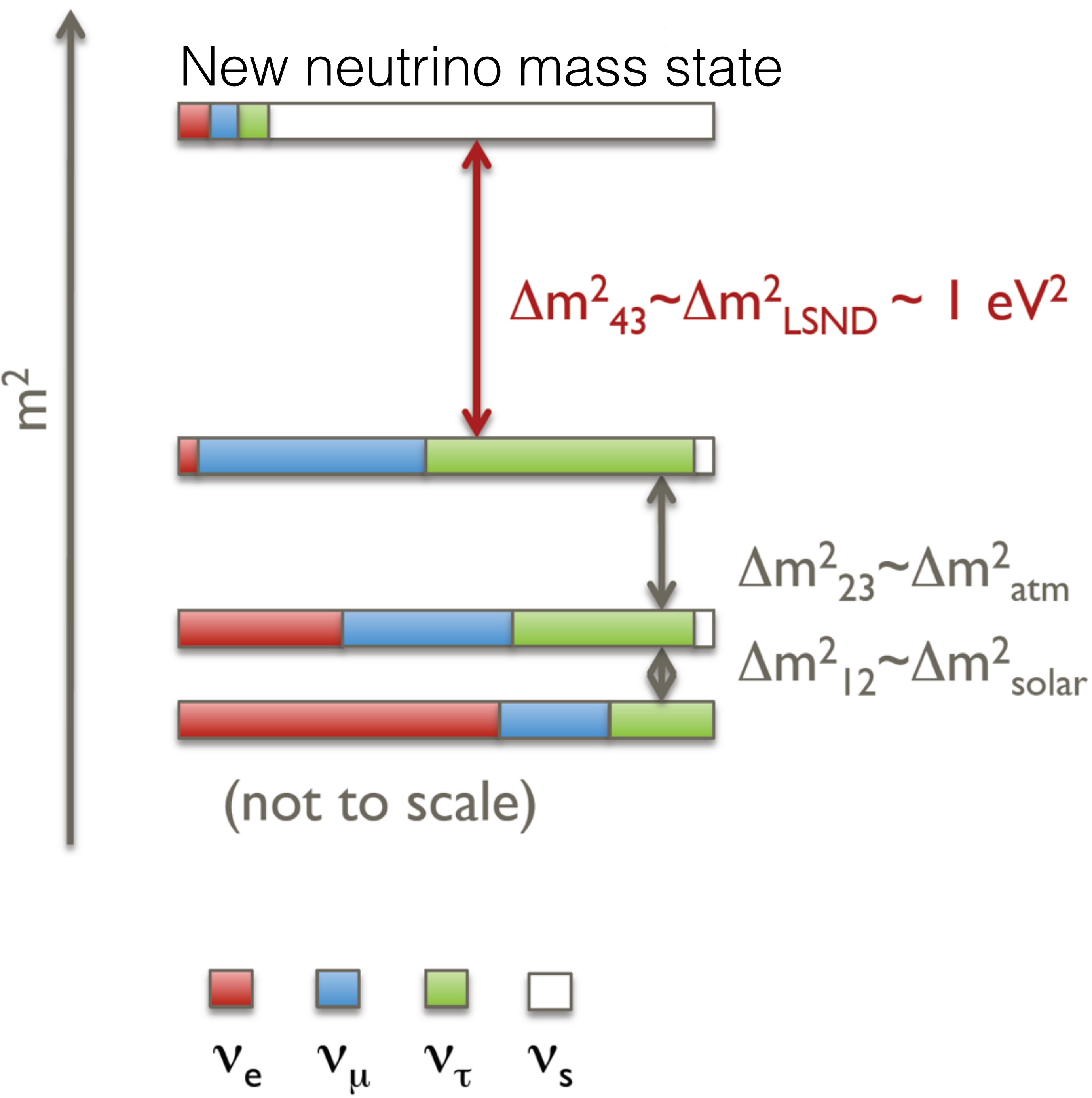


We know the Z boson decays into three neutrinos.

- Can participate in oscillations with active flavors.

$$\nu_e \to \nu_s \quad , \quad \nu_\mu \to \nu_s \quad , \quad \nu_\tau \to \nu_s$$

Where does it fit?



- The observation of neutrino mass implies that there can be sterile, right-handed neutrinos. So, this is not unexpected.
- This right handed neutrino can either directly provide a Dirac mass term or it can mediate the seesaw mechanism.
- A light sterile neutrino would have profound effects on:
    - Radiation density in the early universe.
    - Supernova evolution.
    - Possible warm dark matter candidate?
    - Active neutrino oscillations and particle physics in general.

Present status of the light sterile neutrino

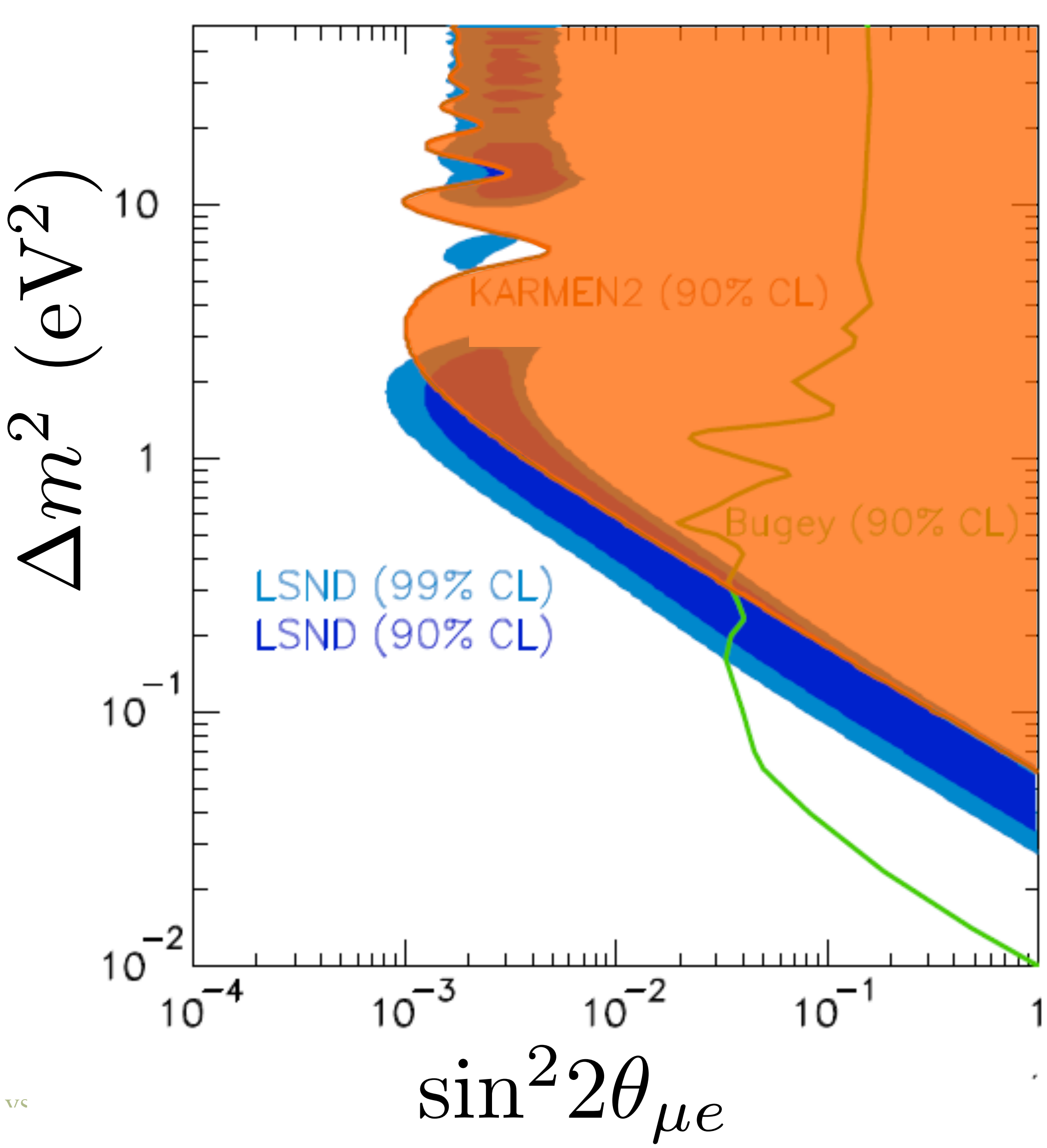
- A number of experiments hint at a new neutrino mass eigenstate around 1 eV.
- A definitive probe of this parameter space is necessary.
- It would be great if the solution we develop could be used toward the future of the field.

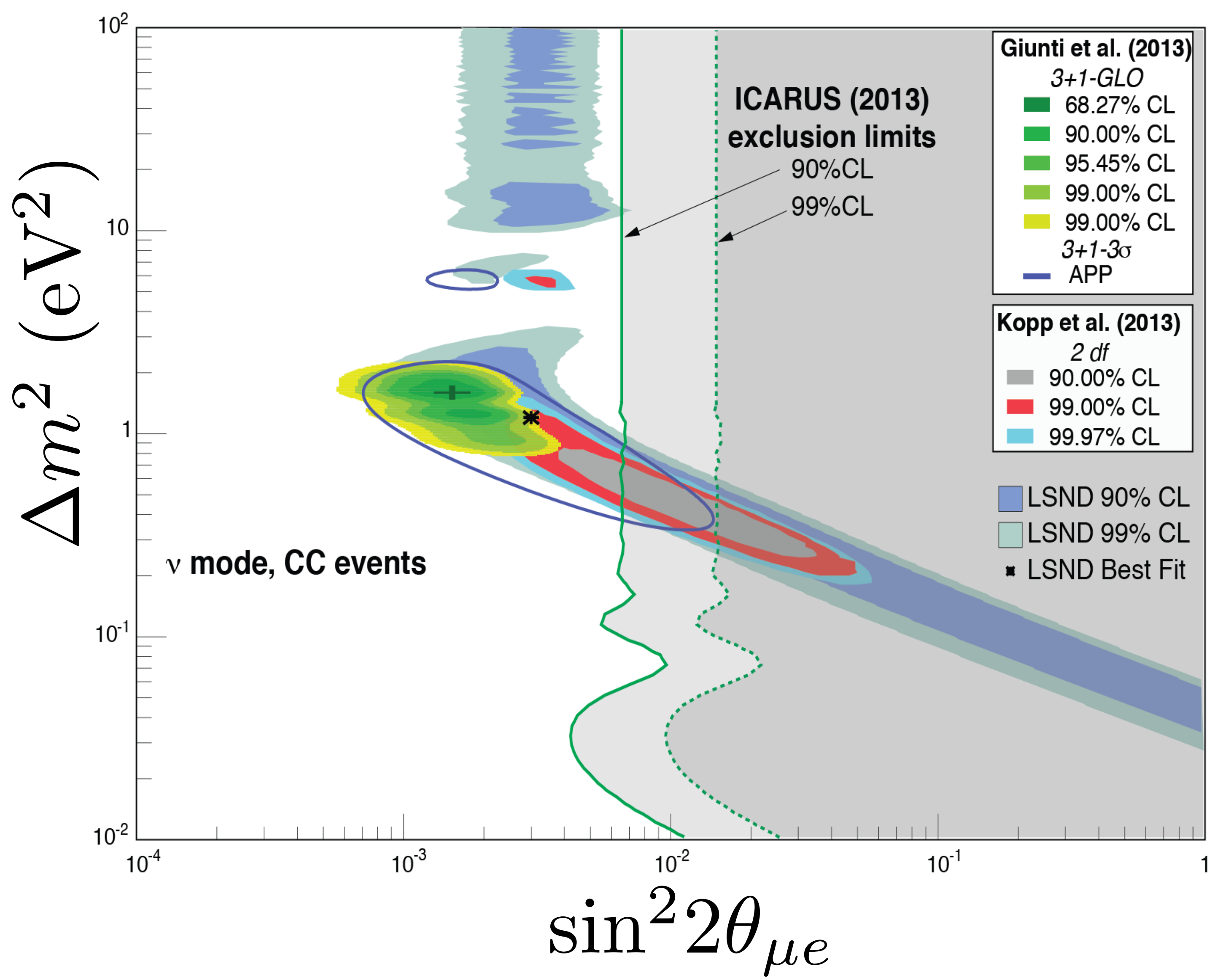
“How do you know it’s a sterile neutrino, if it’s anything at all?”

- We don’t. But, if we want to figure out what (if anything) is going on, we need to probe the parameter space.
  - Parameter space can be defined here as: **(Δm^2, $\sin^2 2\theta$)** and/or **(L, E_ν)** and/or **(E_ν)**.
  - All spaces are interesting and, even in the absence of a sterile neutrino, can teach us about neutrinos for the future of the field!

Probing the parameter space, in (Δm^2, $\sin^2 2\theta$)

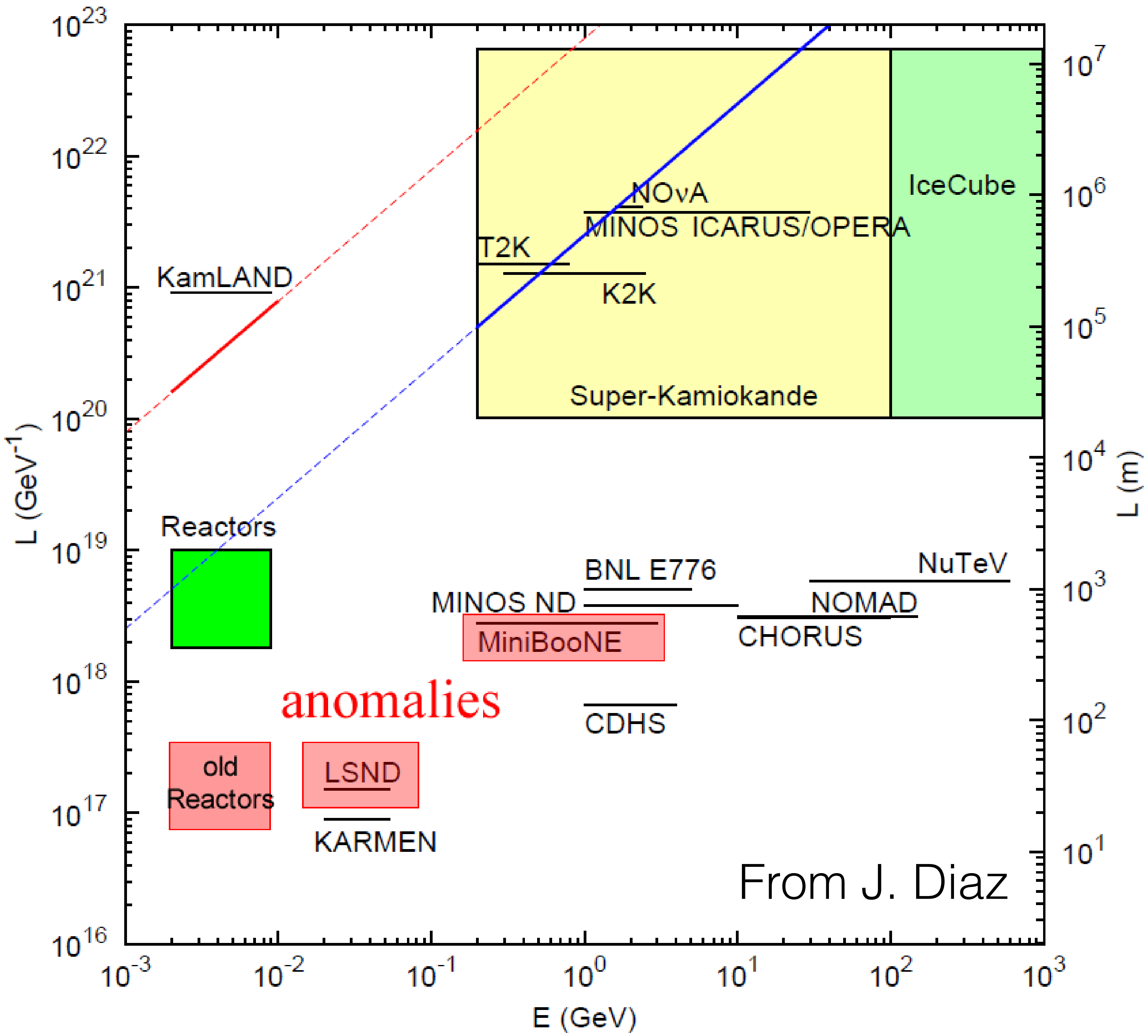
(hypothesis: anomalies may be due to one or more sterile neutrinos)





Probing the parameter space, in (L,E$_\nu$)

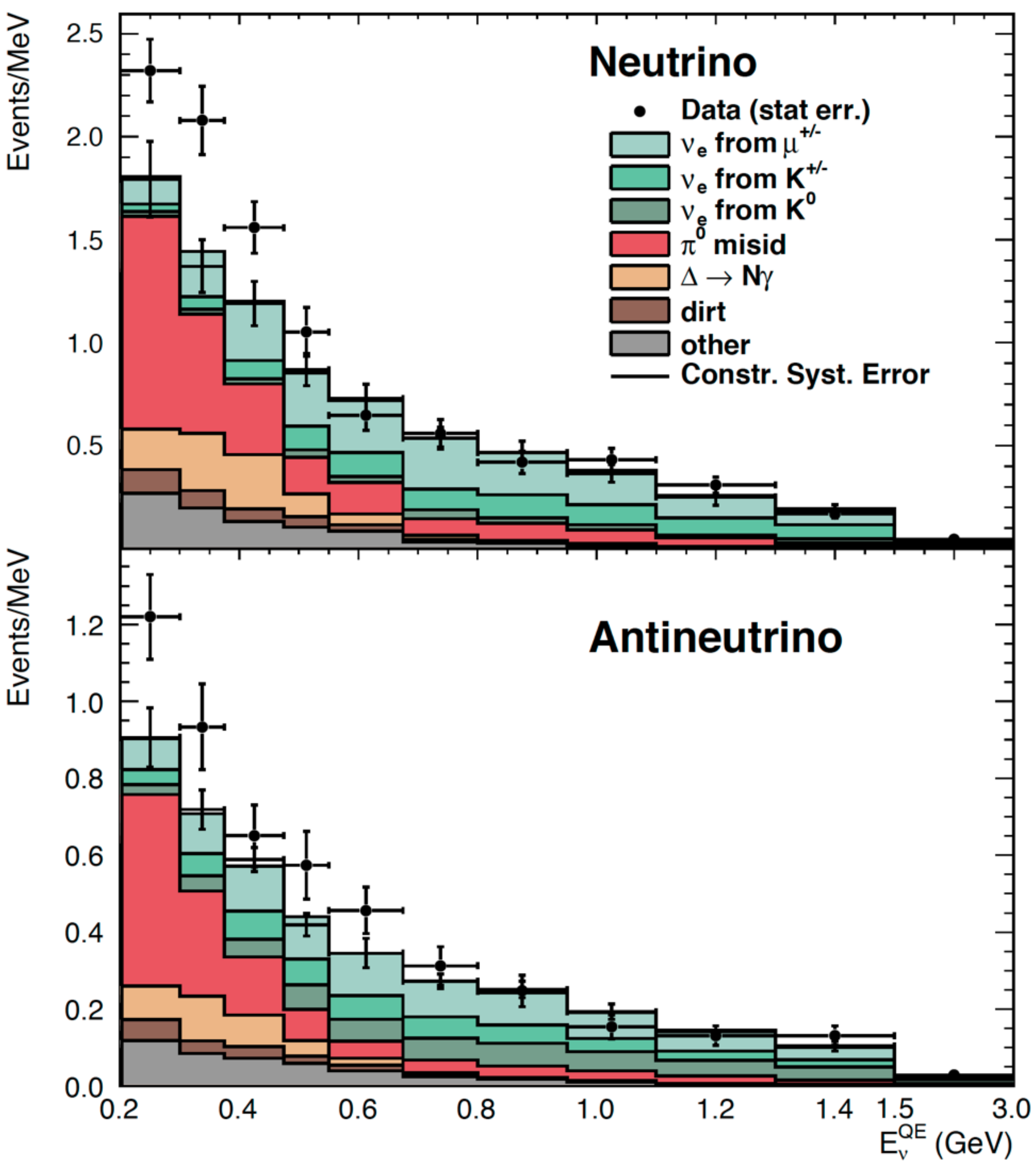
(hypothesis: anomalies may be due to Lorentz violation or something else exotic)



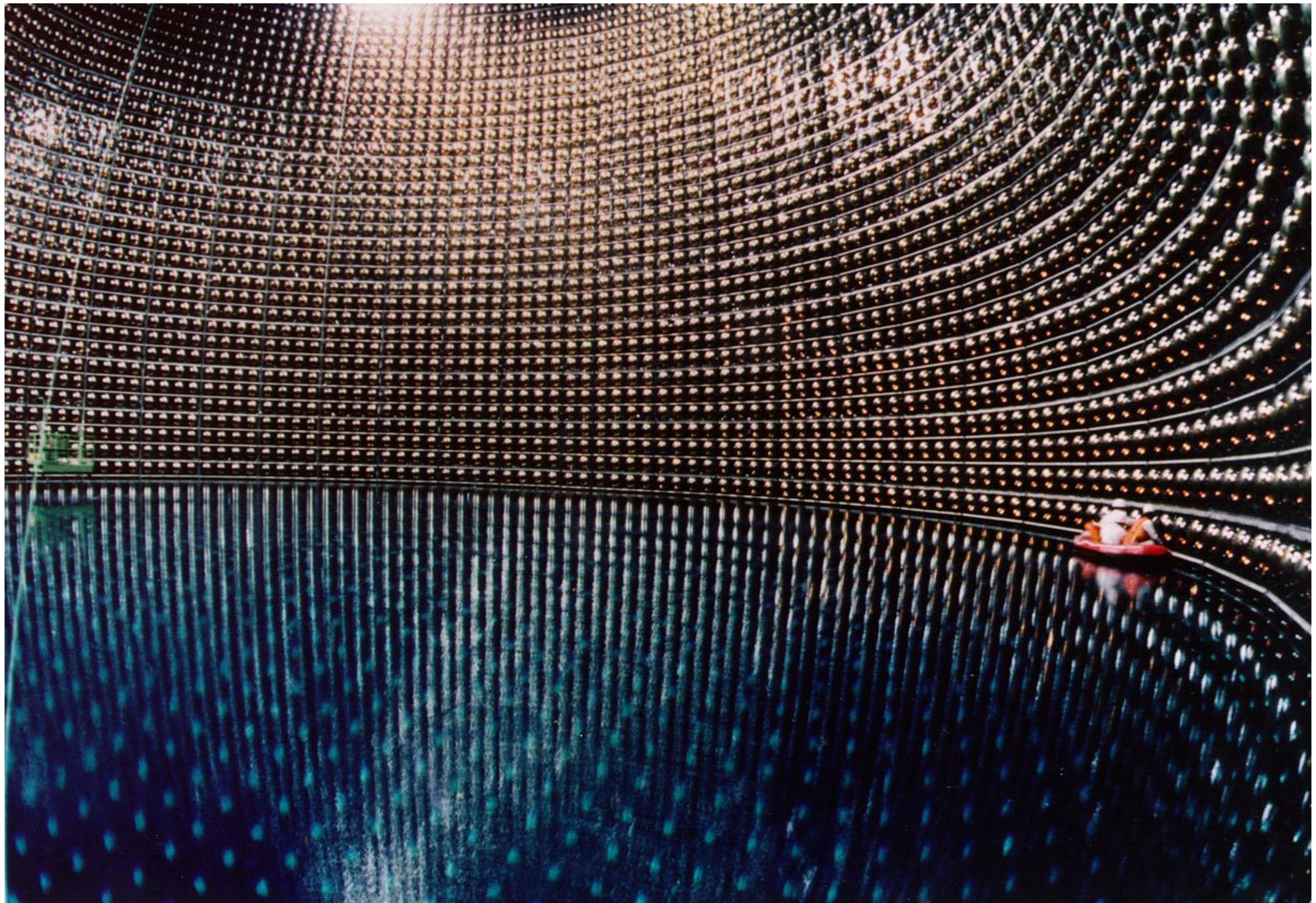
- Unconventional energy dependent oscillation behavior (mixing due to more than just mass) is expected in a number of exotic scenarios.
- Maybe we have just 3 neutrinos and some other (profound) physics is taking place!

Probing the parameter space, in (E_ν)

(hypothesis: anomalies may be due to lack of neutrino interaction understanding, an underestimated background, energy reconstruction issues, or some other systematic)

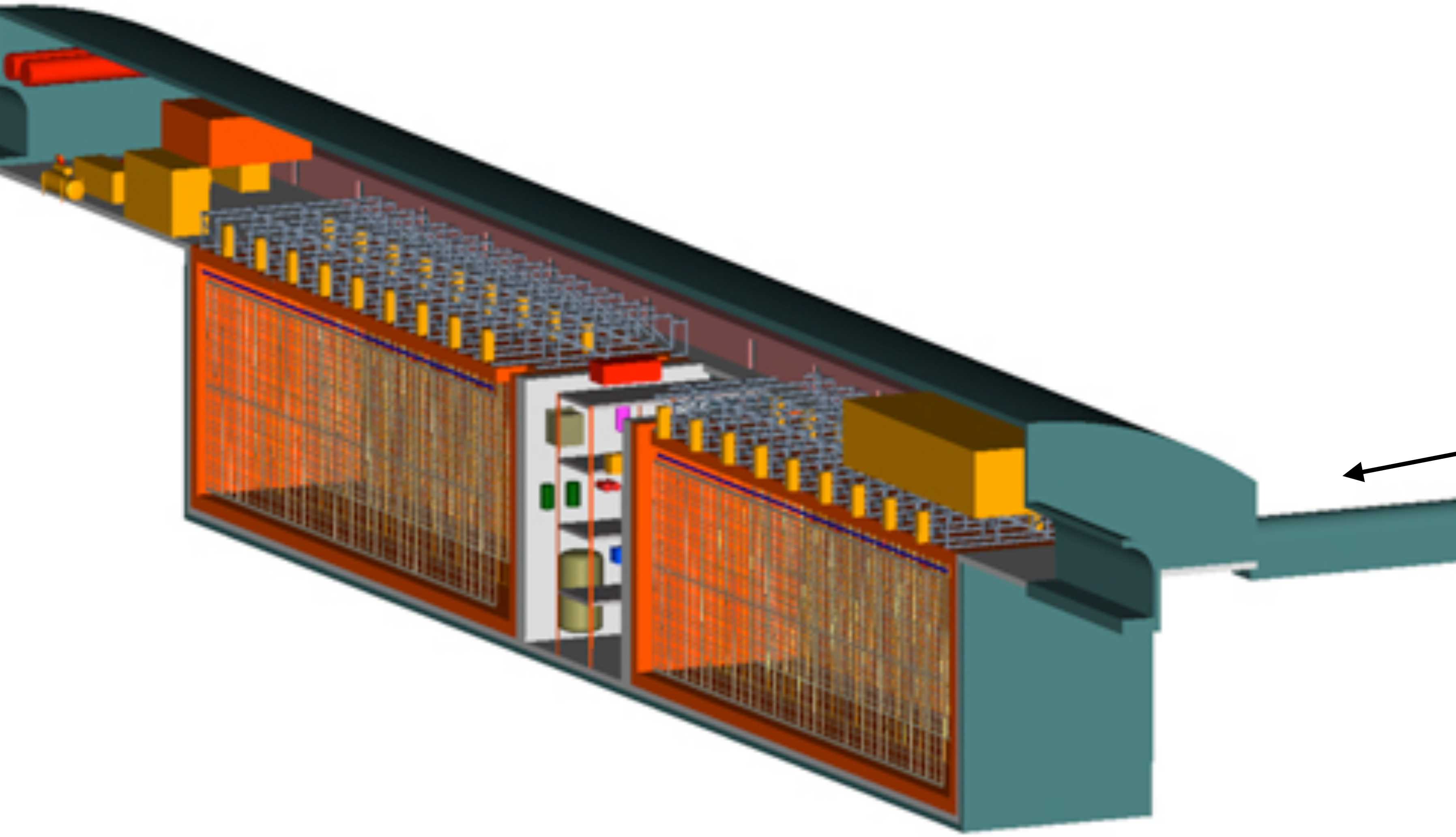


This hypothesis and its resolution may be important for long baseline experiments!



The future of the accelerator-based program

Light sterile neutrino (or something else we don't understand)



The future of the accelerator-based program

(a “super shark”, capable of living in 87 K)

Light sterile neutrino (or something else we don’t understand)

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How to probe neutrino oscillations?

1. Make a lot of neutrinos*.
2. Count them.
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How to probe neutrino oscillations?

1. Make a lot of neutrinos*.
2. Count them.
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*Choose a smart baseline (L) and energy (E) so that you are probing the relevant oscillation parameter space (Δm^2, θ).

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\,\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right)$$

e.g. $\frac{L}{E} \sim 1\ \frac{\mathrm{m}}{\mathrm{MeV}}$ probes $\Delta m^2 \sim 1\ \mathrm{eV}^2$

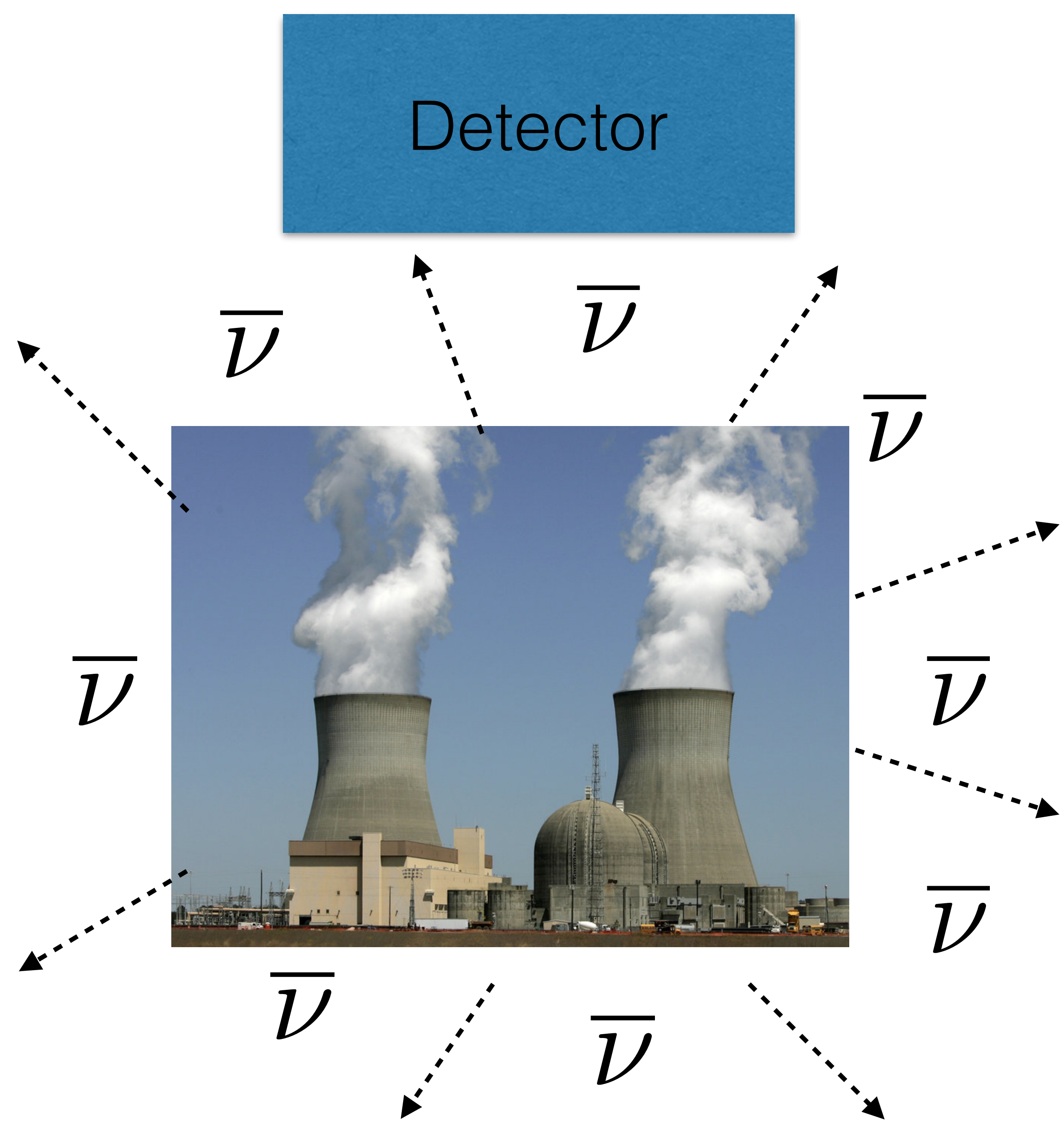
Reactor

Concept: put a detector very close to a reactor

Considerations:

- Fast neutron background
  - PSD can be used to differentiate proton recoil from signal positron.
  - Reactor-off data and overburden can help with nature-induced bkgd.
  - Reactor-induced neutrons are difficult to account for.
- Compact core is optimal.

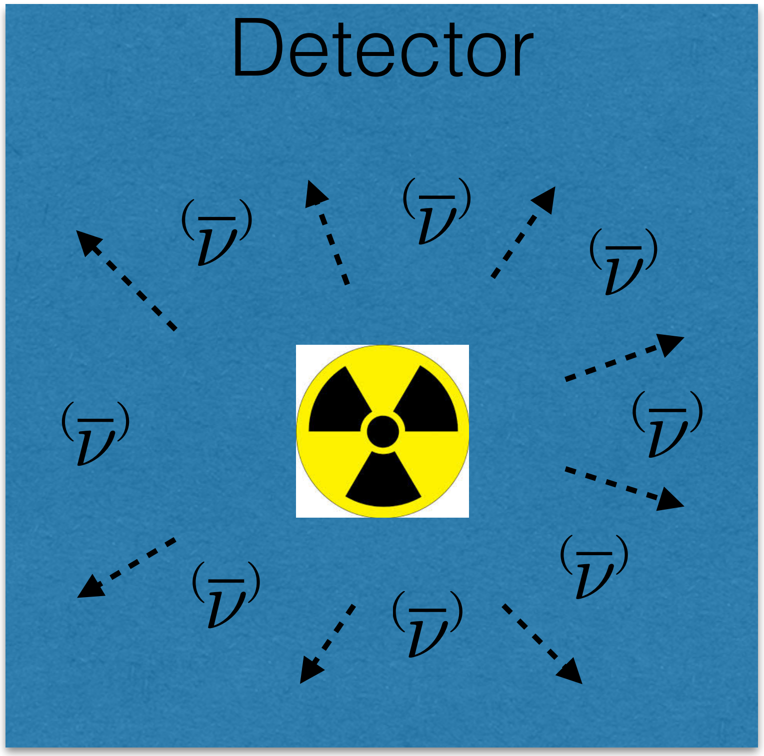
$$\overline{\nu}_e \to \overline{\nu}_x \ ?$$



Source

Concept: put a hot (MCi-scale) source inside or near a planned or existing low-E neutrino detector

$$\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_x \; ?$$



Considerations:

- Source production, transport, and handling.
- Source inside detector is optimal but challenging.
- Vertex and energy resolution are key.

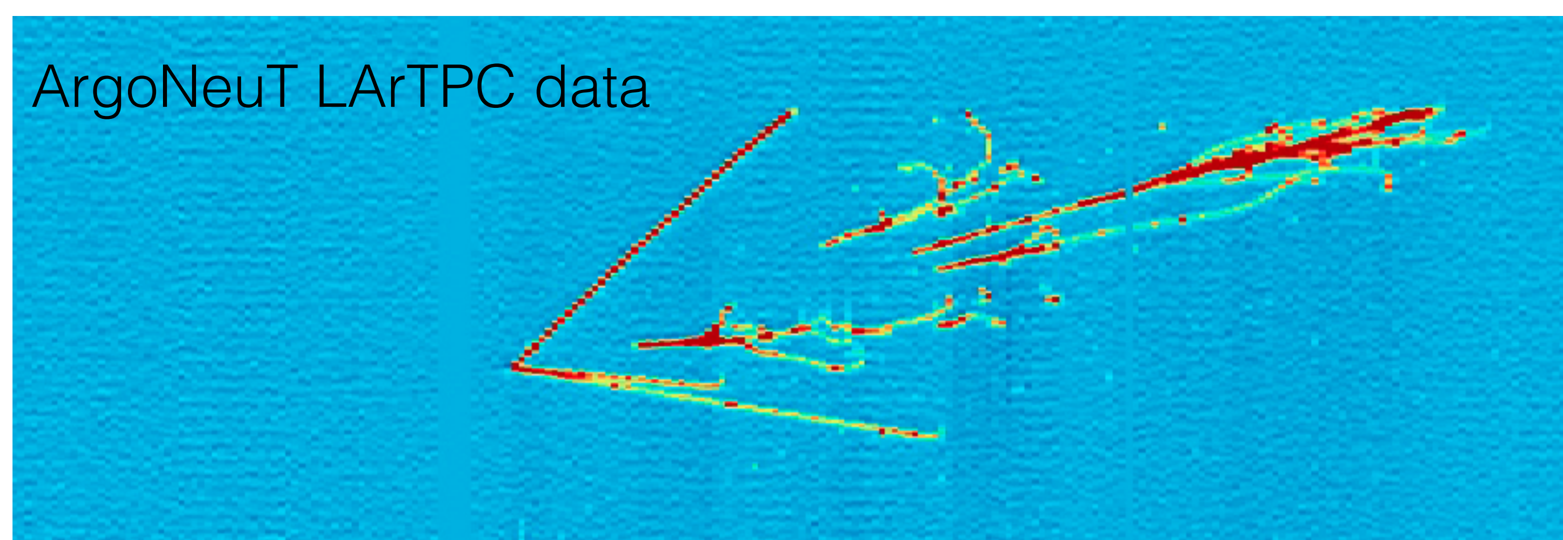
Accelerator decay-in-flight

Considerations:

- Flux (intrinsic electron contamination and absolute normalization) is hard to determine. A near detector helps.
- Strong background ID (e.g. neutral current events that look like signal) requires advanced tech.
- Need a big far detector. LSND best fit osc. probability is ~0.001.

MicroBooNE

- MicroBooNE is a 90 ton LArTPC at FNAL's Booster Neutrino Beamline. First data is in 2015!
- Along with vital neutrino cross section measurements and LArTPC R&D, MicroBooNE will definitively address the MiniBooNE low-E excess, which may be related to a sterile neutrino.
- Represents the first step in a phased LAr-based program at FNAL to address the sterile neutrino definitively.



(For the uninitiated, this is a quote from "Jaws")

LAr1-ND MicroBooNE ICARUS (T150+T600)

Combining forces!

An international program at Fermilab's BNB (and NuMI off-axis) likely featuring three detectors by 2018: near, MicroBooNE at mid-distance, and far.

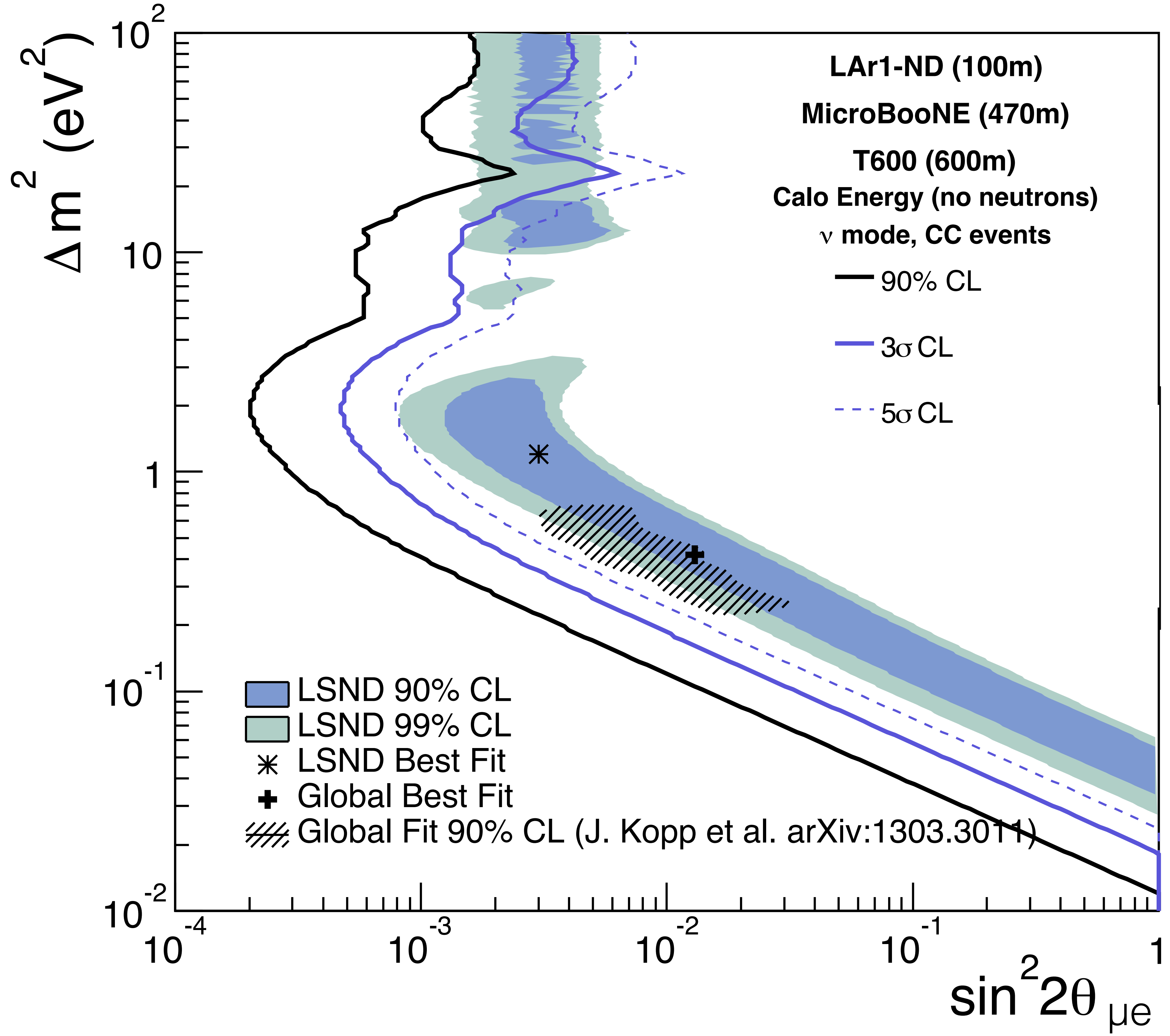
Updates:

The WA104 R&D activity at CERN is approved and will rebuild the T600 and prepare it for beam at FNAL.

The approved T-1053 (LAr1-ND) experiment at FNAL will perform needed R&D and develop the technical design for the LAr1-ND detector.

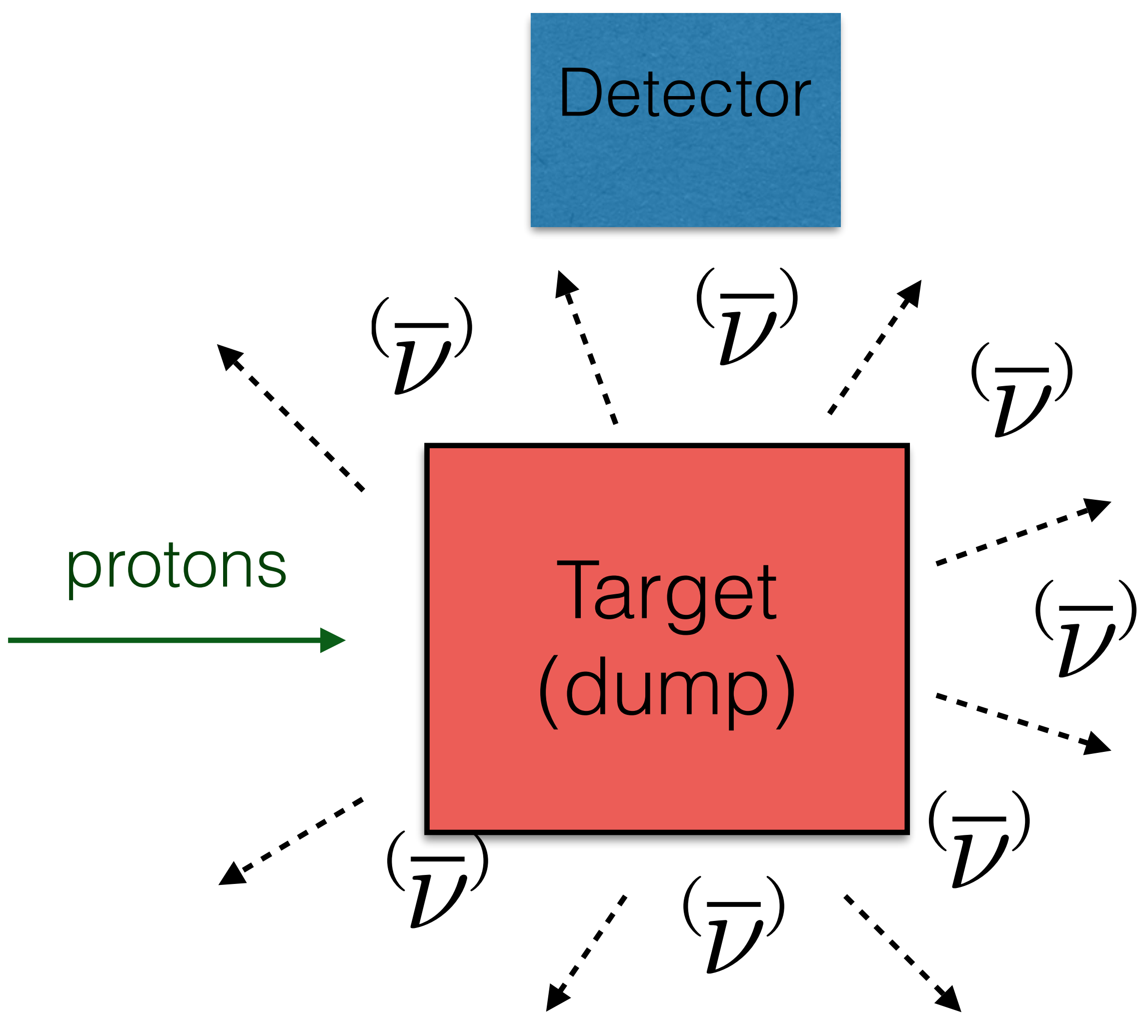
The MicroBooNE detector will be coming online shortly.

Sensitivity of Triple-LAr @ FNAL



Accelerator decay-at-rest

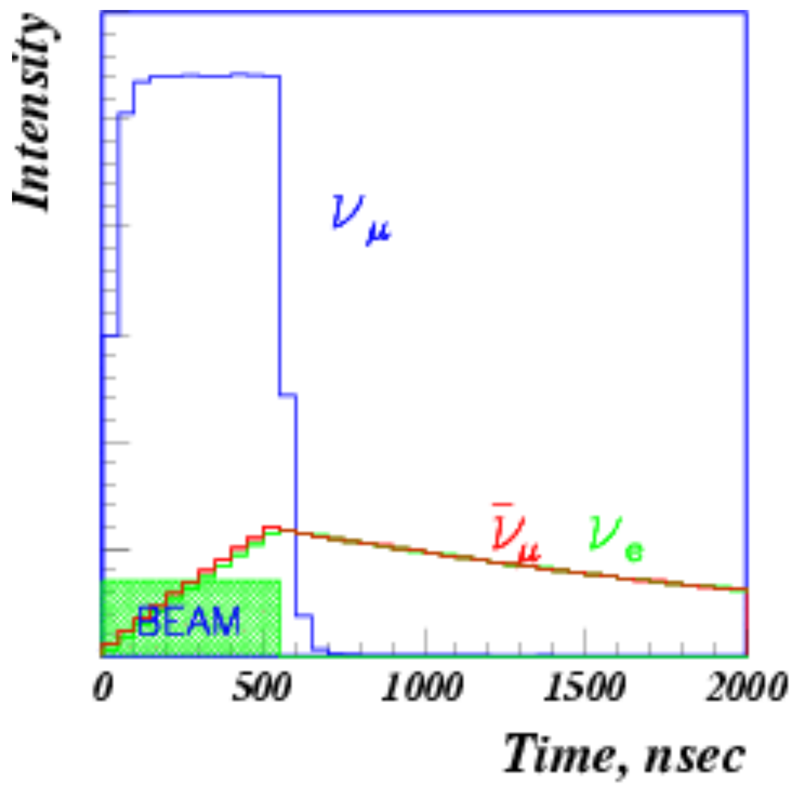
(LSND-style)



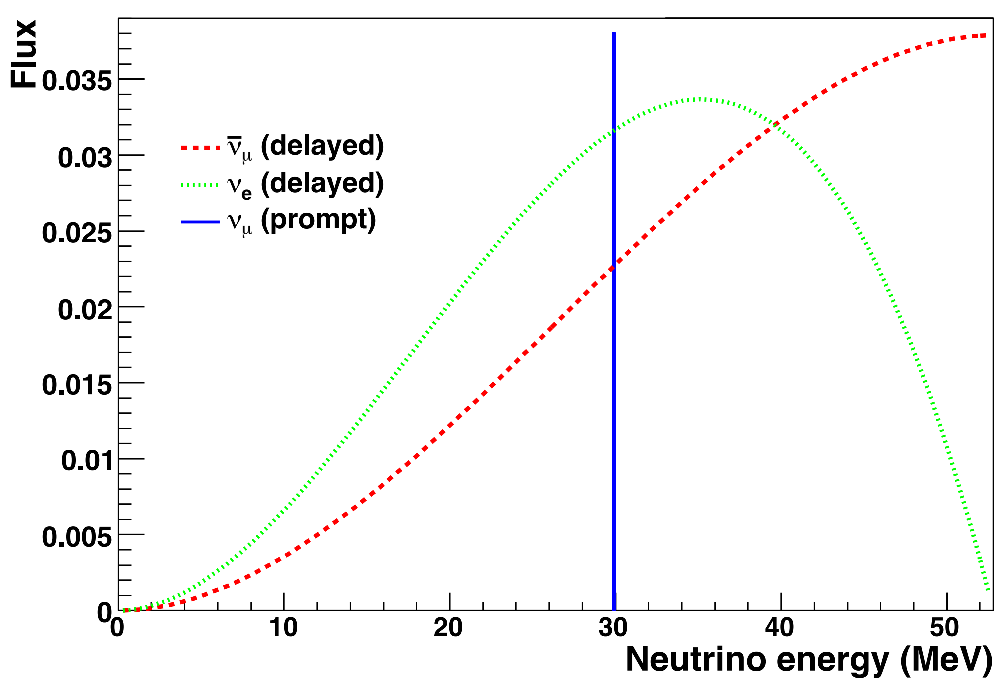
$$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e \ ?$$

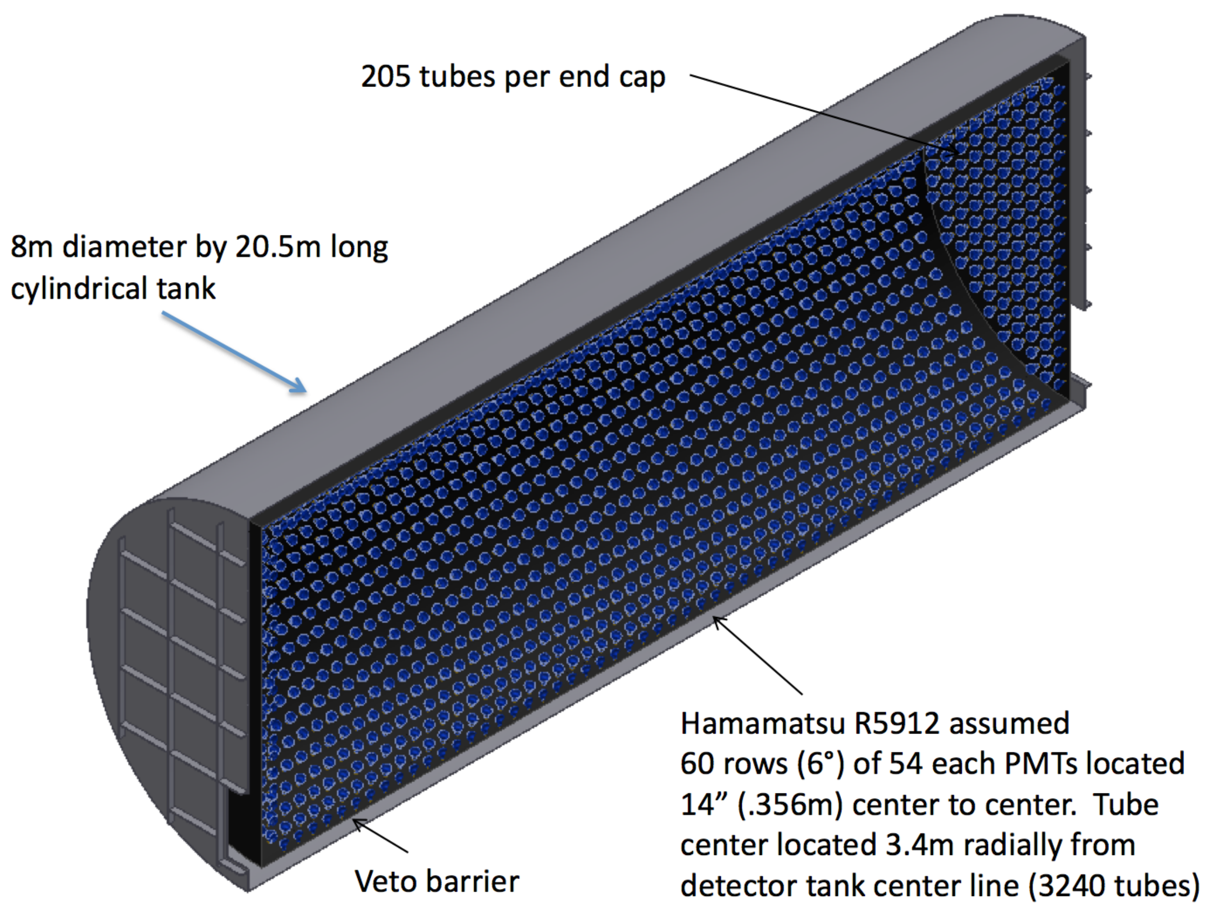
$$\nu_e \to \nu_x \ ?$$

OscSNS



- A proposed LSND-style decay-at-rest experiment at the 1.4 MW SNS (1 GeV protons on an Hg target).
- Can provide *definitive* coverage of the sterile neutrino region with an 800 ton LS detector, 60 m away.

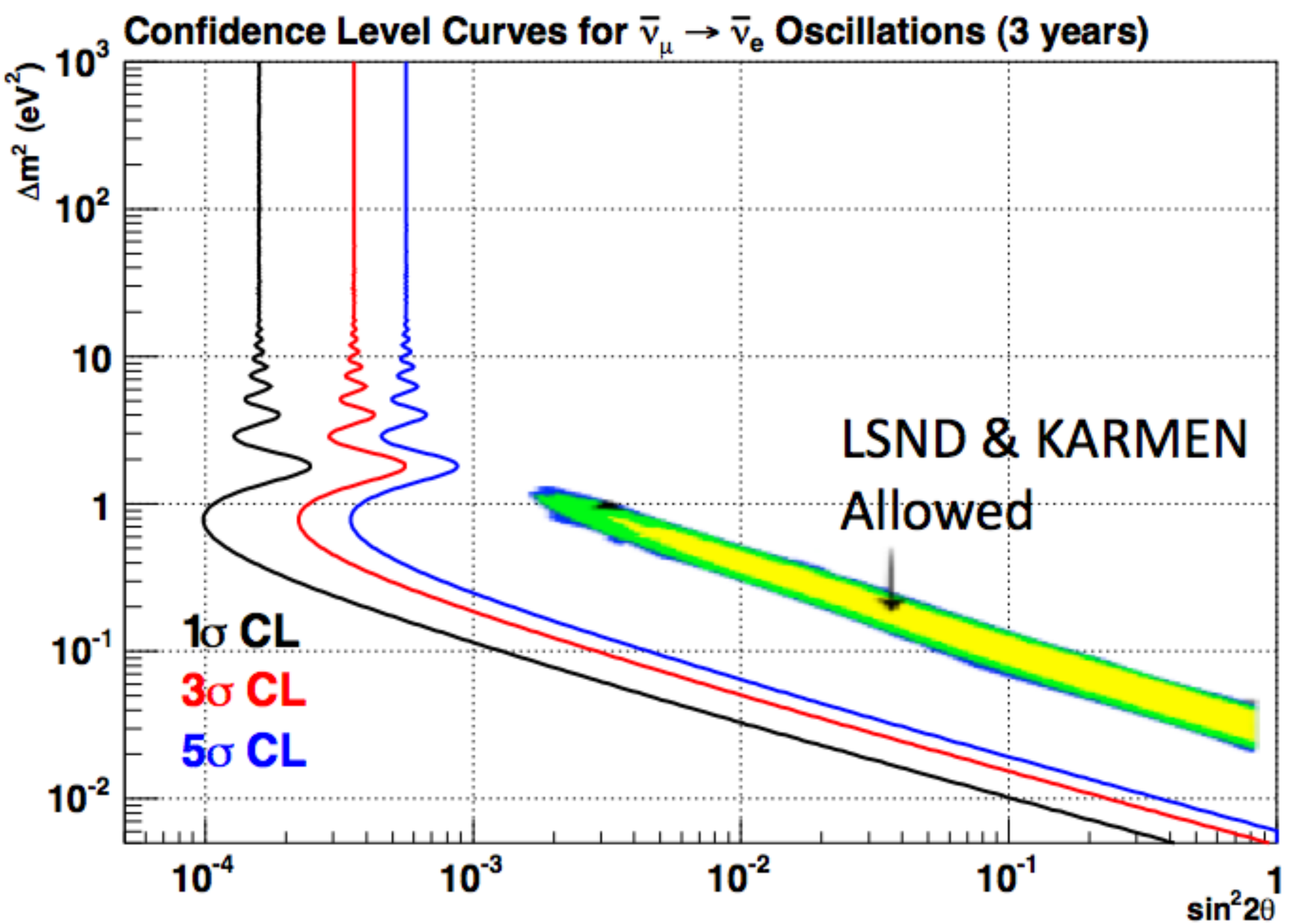




OscSNS seems to solve all of the usual quibbles about LSND

	LSND	OscSNS	Notes
Baseline	30 m	60 m	Reduced in-beam background
Orientation	Detector in front of beam	Detector behind beam	Reduced in-beam background
Beam power	0.8 MW	1.4 MW	
Beam pulse	600 μs,120Hz	695 ns, 60 Hz	Reduced steady-state background
Beam kinetic energy	798 MeV	1000 MeV	
Detector mass	167 ton	800 ton	
Detector technology	Liq. scint. w/ 25% photocoverage	Liq. scint. w/ 25% photocoverage	Better PMT QE expected in OscSNS

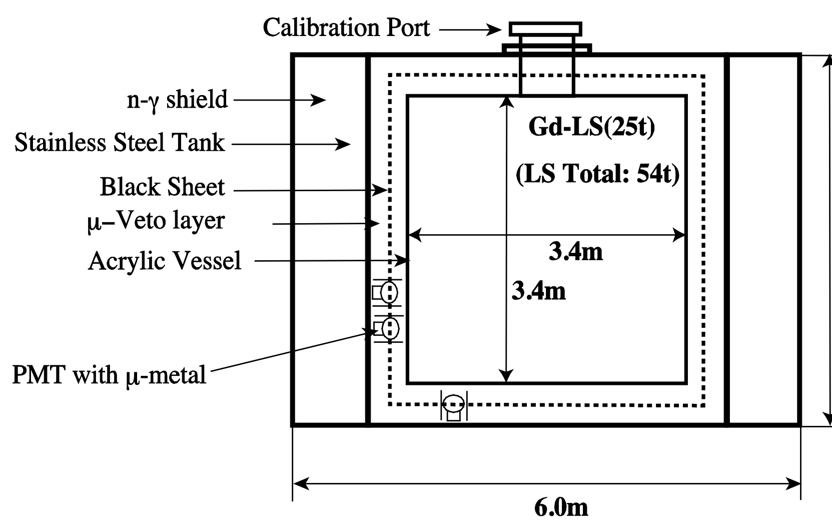
OscSNS sensitivity

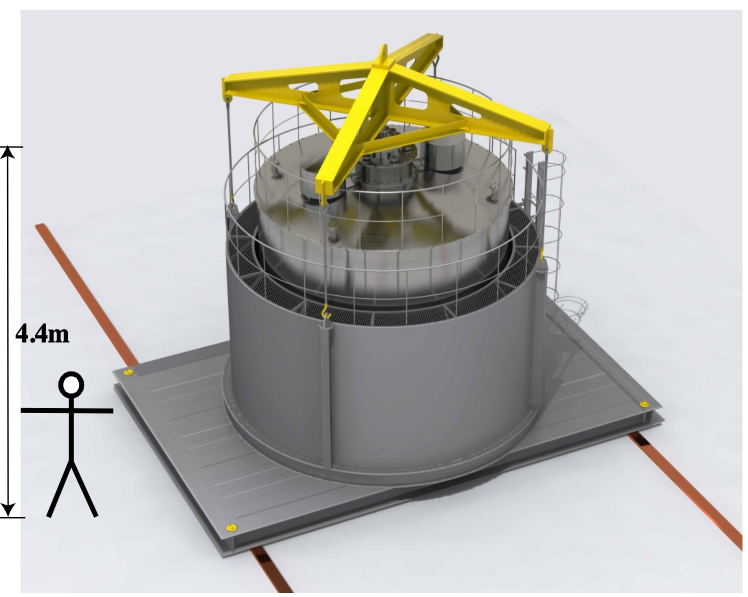


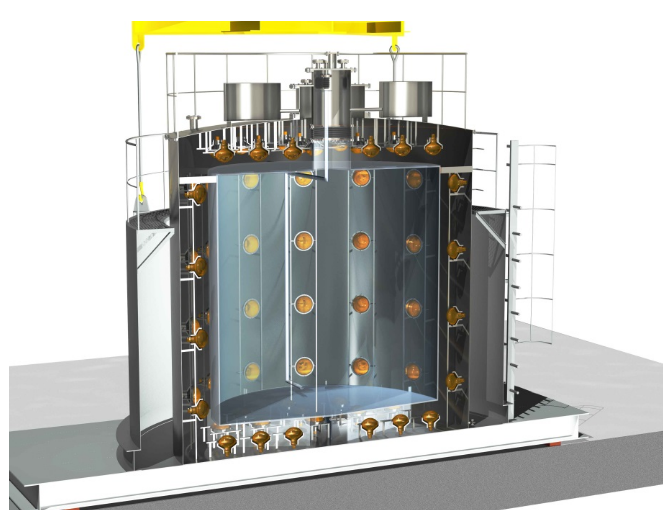
OscSNS White Paper, arXiv:1307.7097

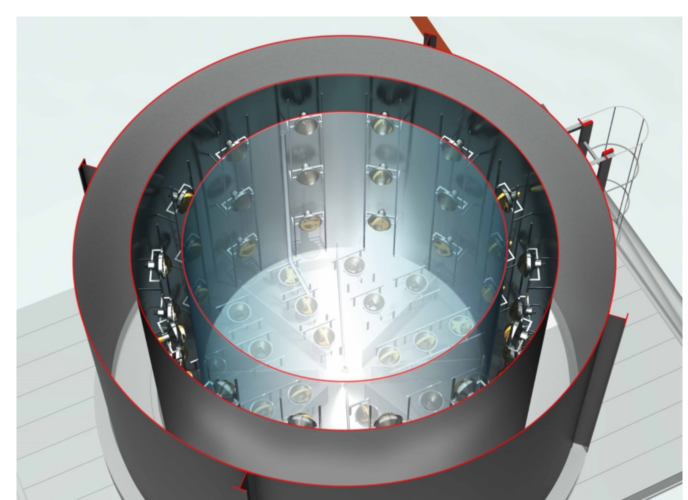
JPARC-MLF

- The JPARC-MLF proposed experiment is very similar to OscSNS.
- An eventually 1 MW spallation source, with 3 GeV protons on a Hg target.
- Phased approach with “Phase 1” proposal to put 2x25ton Gd-LS detectors 17 m away from the source to do an LSND-style experiment.



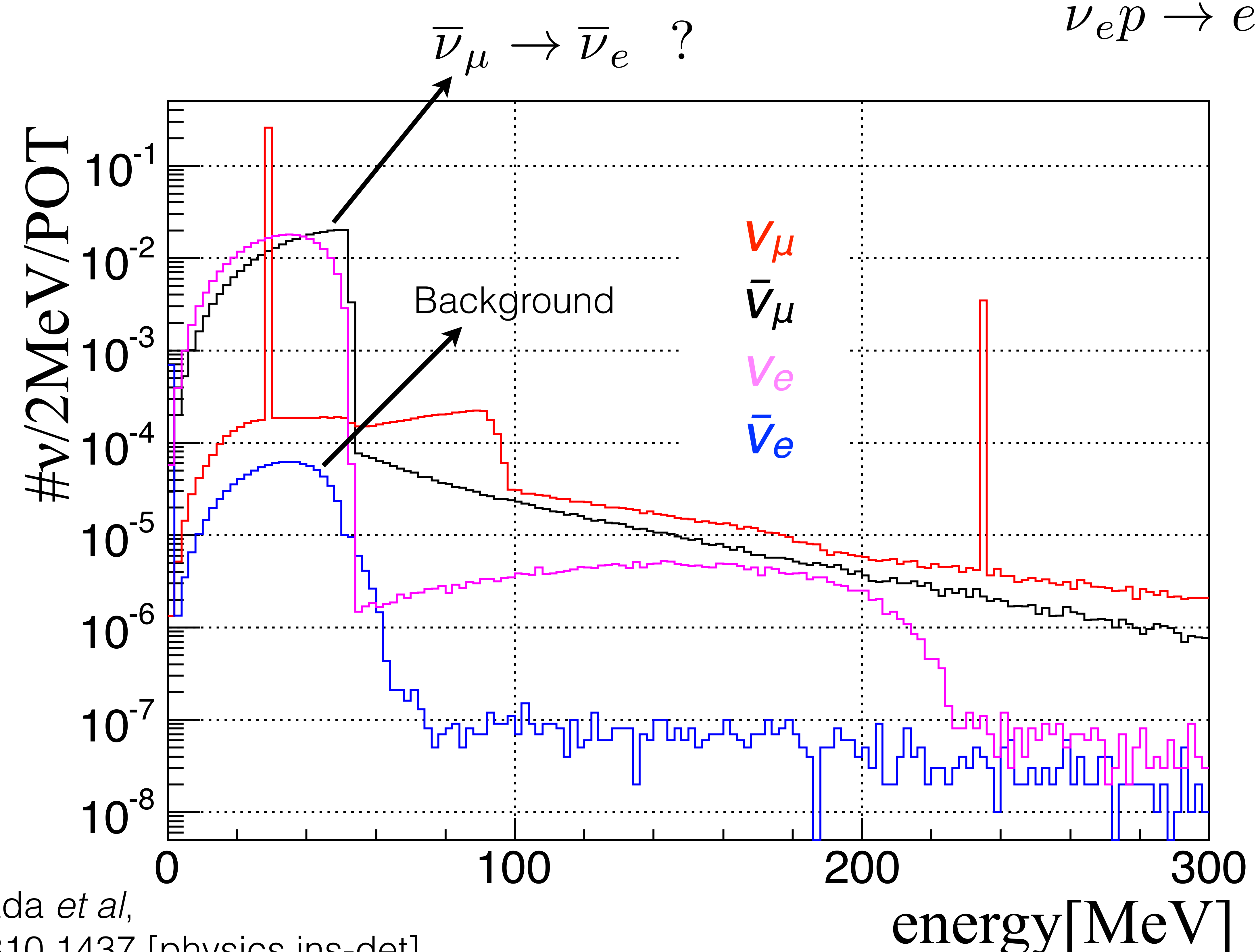






LSND-style

Detect with:
$\overline{\nu}_e p \to e^+ n$

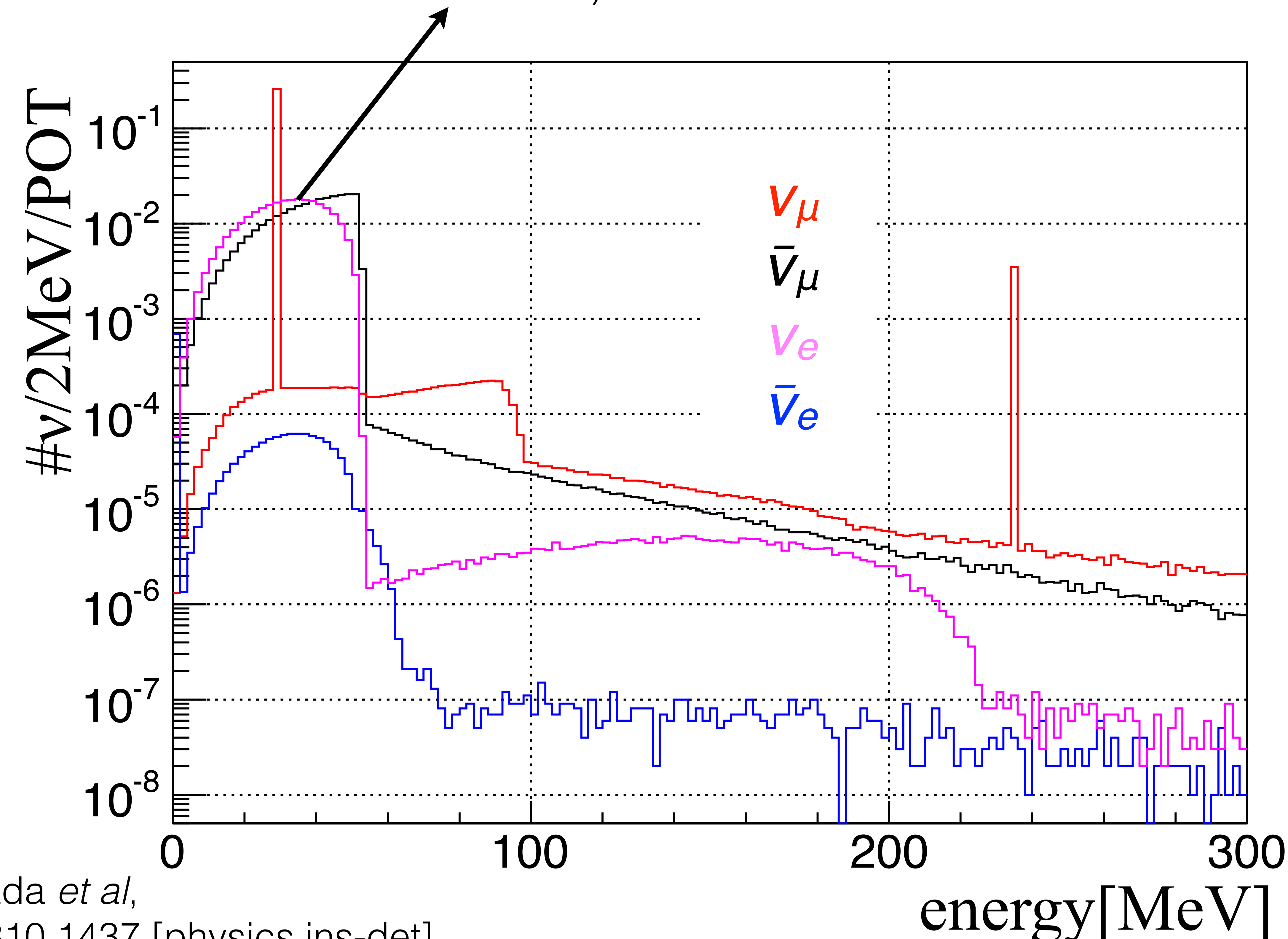


M. Harada *et al*,
arXiv:1310.1437 [physics.ins-det]

Electron disappearance

$\nu_e \rightarrow \nu_{\not e}$?

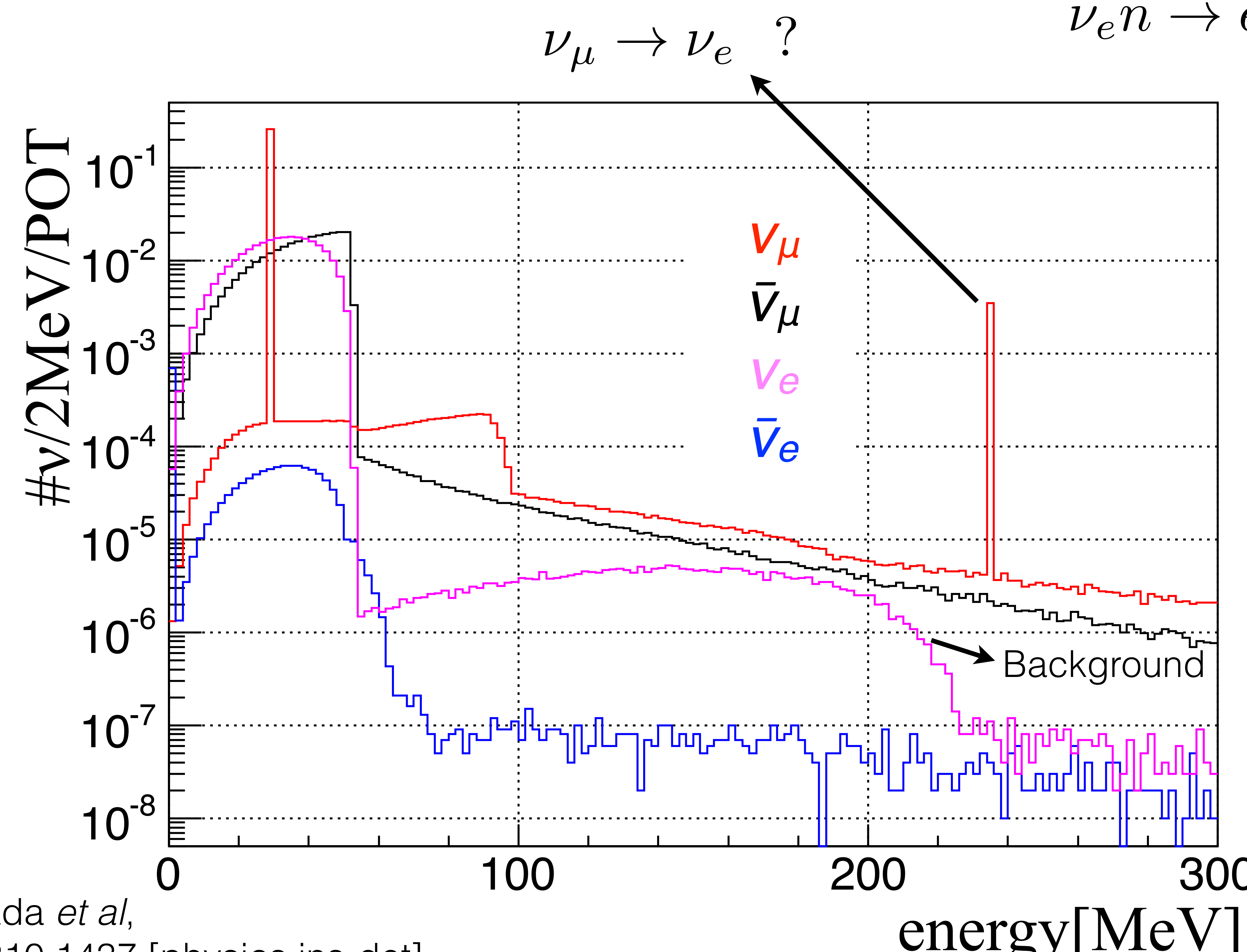
Detect with:
$\nu_e \; ^{12}C \rightarrow e^- \; ^{12}N_{gs}$



M. Harada *et al*,
arXiv:1310.1437 [physics.ins-det]

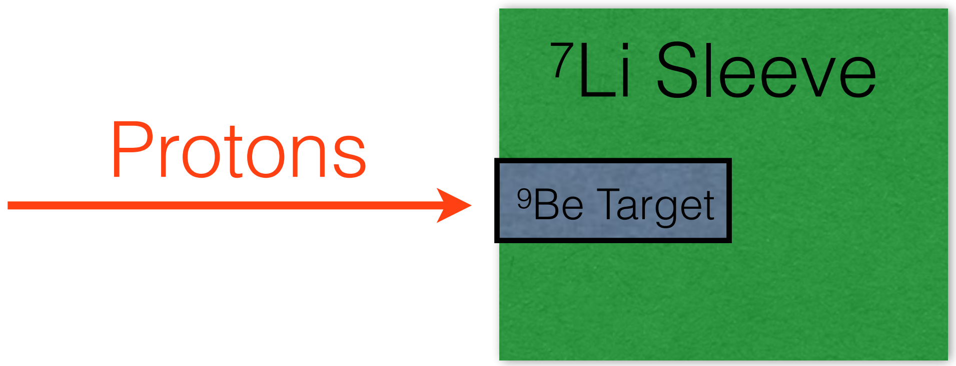
Kaon decay-at-rest

Detect with:
$\nu_e n \rightarrow e^- p$



M. Harada *et al*,
arXiv:1310.1437 [physics.ins-det]

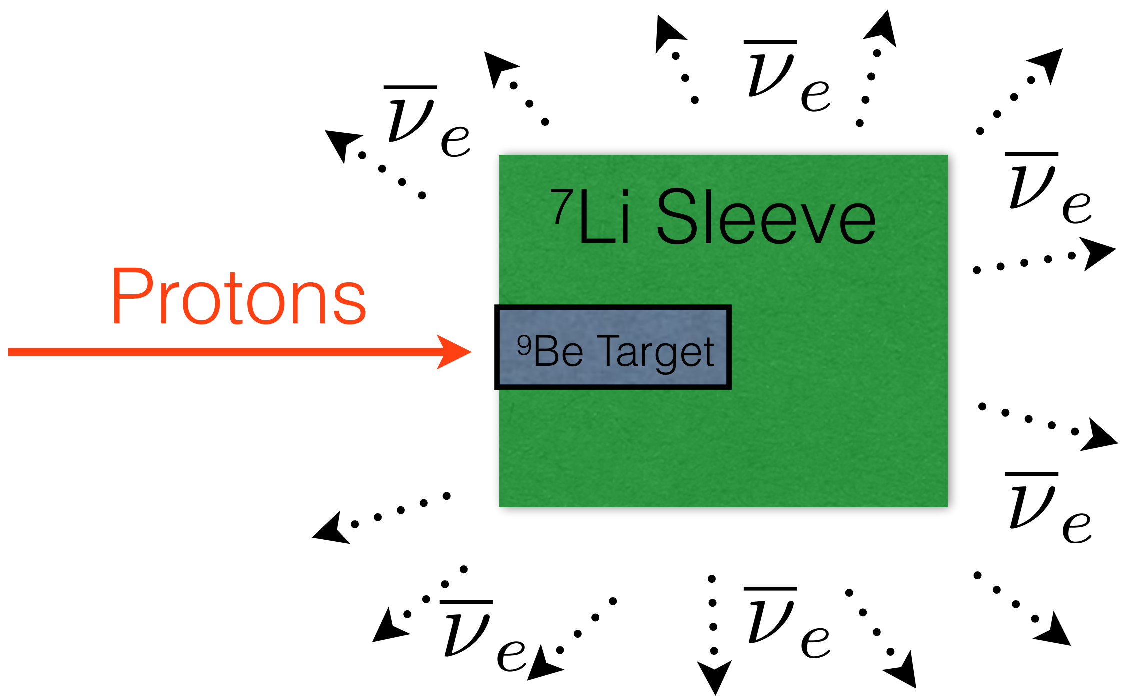
IsoDAR



$$p + {}^{9}\mathrm{Be} \rightarrow \boxed{{}^{8}\mathrm{Li}} + 2p$$

$$p + {}^{9}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + n$$
$$n + {}^{7}\mathrm{Li} \rightarrow \boxed{{}^{8}\mathrm{Li}} + \gamma$$

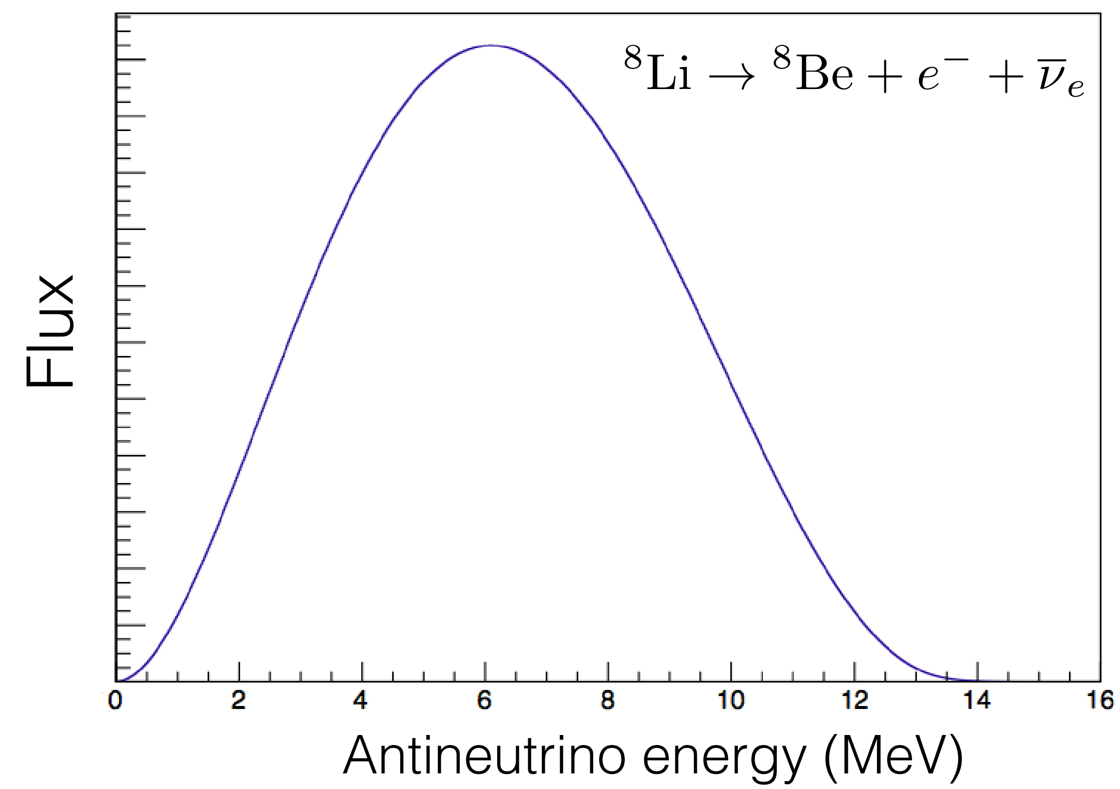
IsoDAR

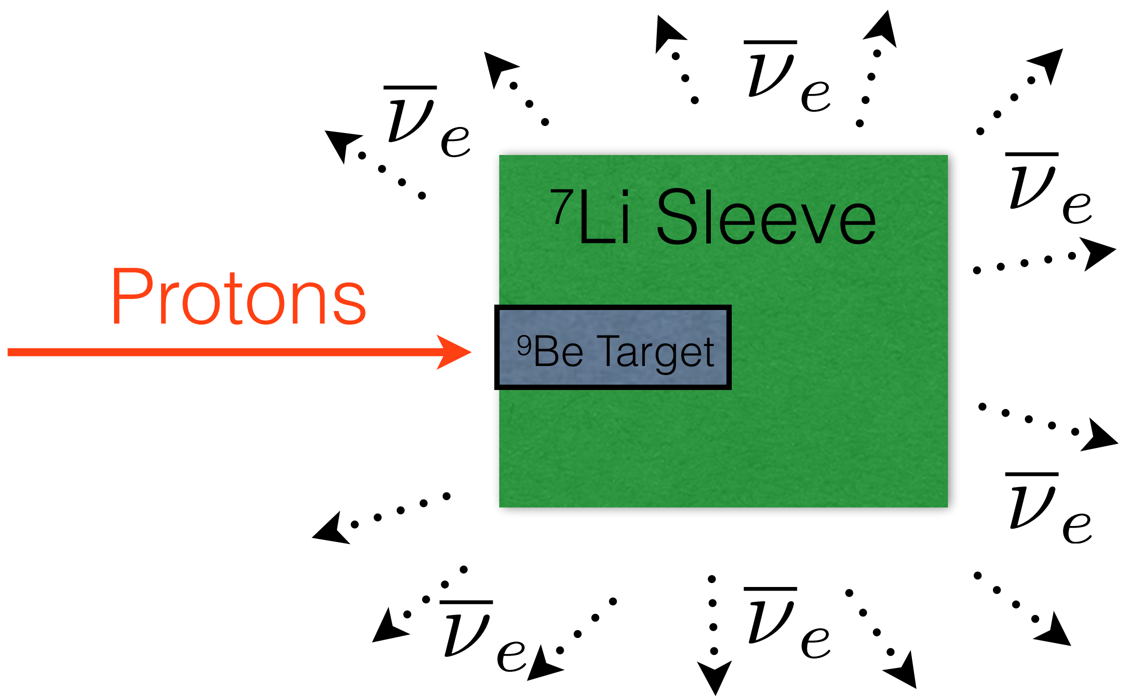


$$p + {}^9\mathrm{Be} \rightarrow \boxed{{}^8\mathrm{Li}} + 2p$$

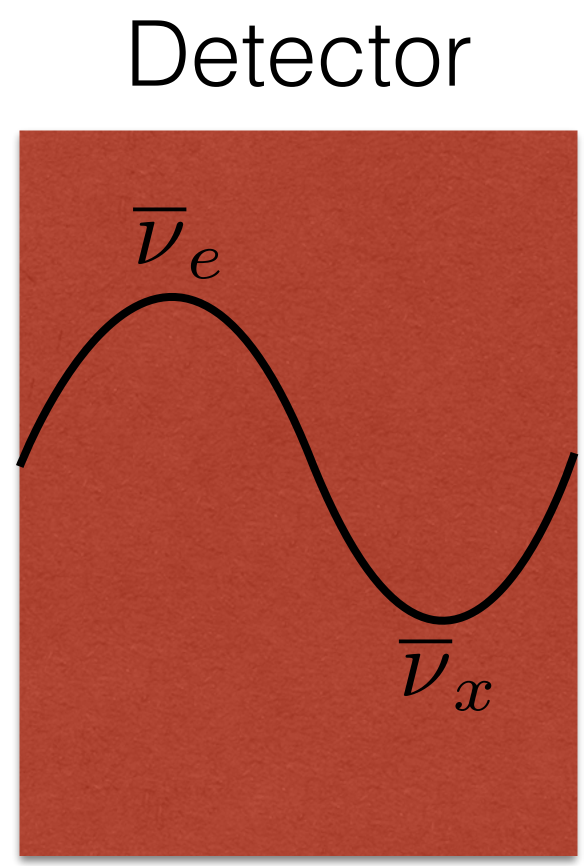
$$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$$
$$n + {}^7\mathrm{Li} \rightarrow \boxed{{}^8\mathrm{Li}} + \gamma$$

$$^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \boxed{\overline{\nu}_e}$$





$$\overline{\nu}_e \rightarrow \overline{\nu}_x \quad ?$$



$$p + {}^{9}\mathrm{Be} \rightarrow \boxed{{}^{8}\mathrm{Li}} + 2p$$

$$\overline{\nu}_e p \rightarrow e^{+} n$$

$$p + {}^{9}\mathrm{Be} \rightarrow {}^{9}\mathrm{B} + n$$

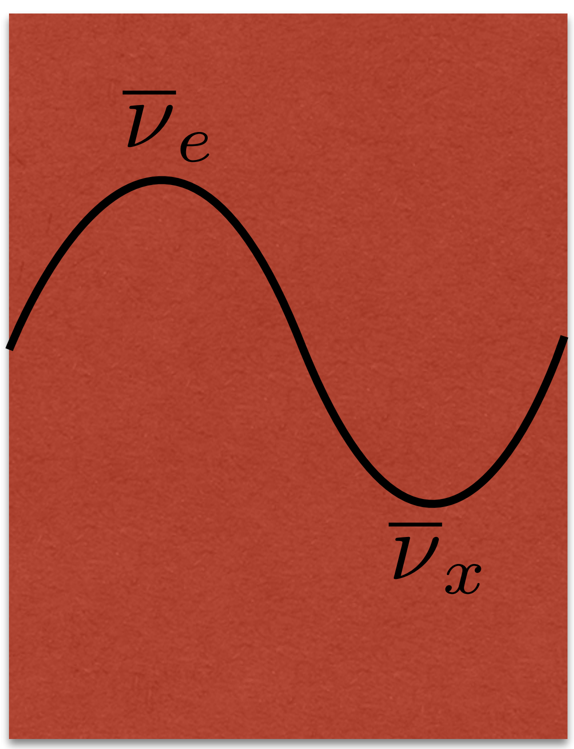
$$n + {}^{7}\mathrm{Li} \rightarrow \boxed{{}^{8}\mathrm{Li}} + \gamma$$

$${}^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be} + e^{-} + \boxed{\overline{\nu}_e}$$

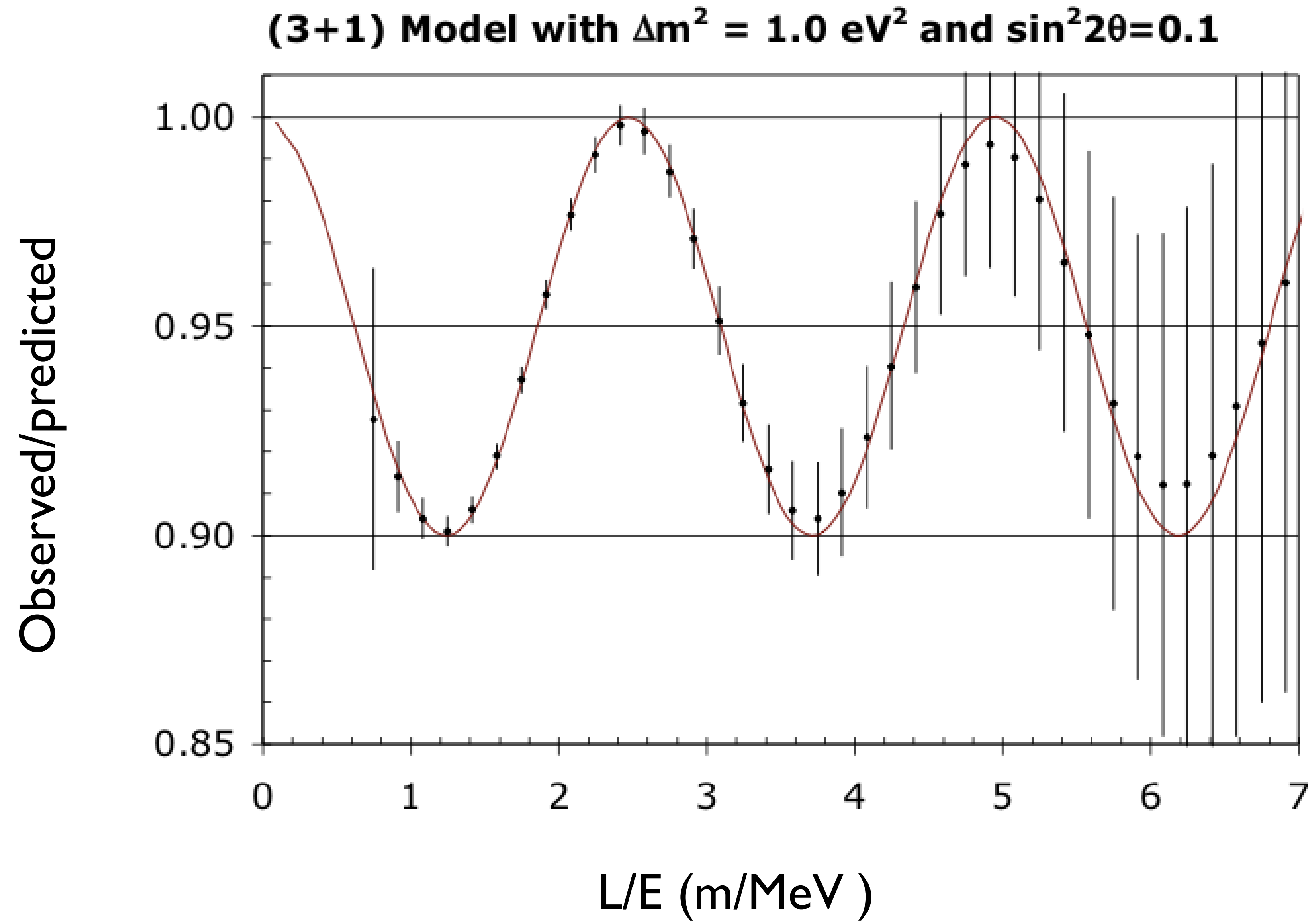
IsoDAR

$$\overline{\nu}_e \rightarrow \overline{\nu}_x \quad ?$$

Detector

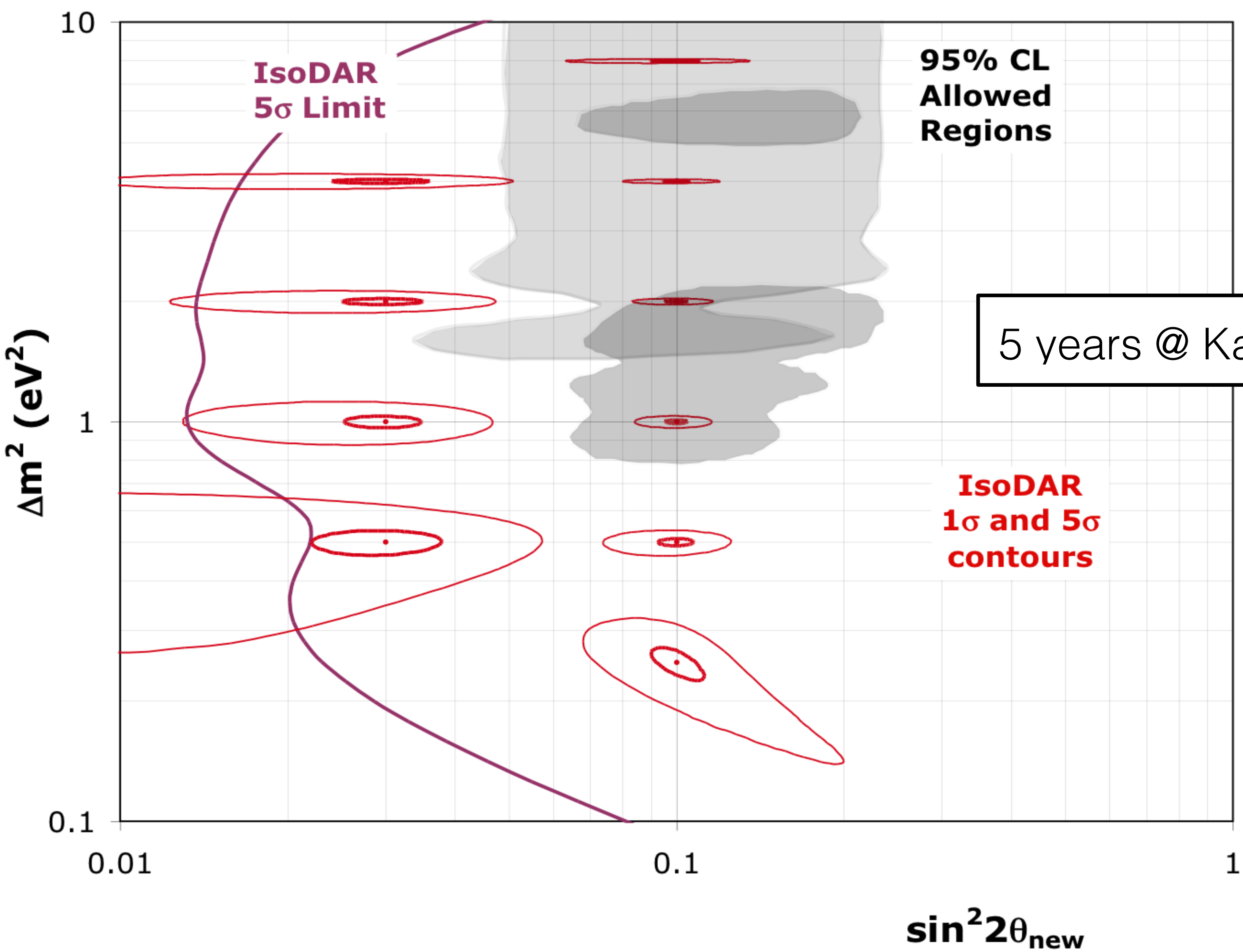


$$\overline{\nu}_e p \rightarrow e^+ n$$



820,000 IBD events in 5 years at KamLAND
(16 m baseline to center of detector)

IsoDAR abilities



5 years @ KamLAND

What is the timeline?

- Reactor and source neutrinos
  - Significant reactor/gallium anomaly coverage within 5 years.
- Accelerator neutrinos
  - Significant LSND/MiniBooNE anomaly coverage within 5 years.

For better or worse, we will be discussing light sterile neutrinos and the “anomalies” for at least 5 more years. In my opinion, 10 is likely.

Conclusions

- **The discovery of a light sterile neutrino would be a monumental result for particle physics and cosmology.**

- The light sterile neutrino issue needs to be resolved.
- A truly definitive resolution is difficult to achieve and will likely require multiple detectors/experiments.
- Regardless if there is a sterile neutrino or not, a lot of important physics and R&D can be provided by these experiments.